RE-ORDER NO. 69-75

QUARTERLY TECHNICAL REPORT

PERIOD 1 JANUARY - 31 MARCH 1969

ELECTRIC THRUSTER POWER CONDITIONER

CONTRACT NO. 952297

HUGHES AIRCRAFT COMPANY
HUGHES DOCUMENT NO. 2228/945

EL SEGUNDO, CALIFORNIA

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ABSTRACT

Quarterly report on JPL Contract 952297 for a 20 CM Electric Thruster Power Conditioner and Support Equipment, describes progress in breadboard fabrication phase.

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FIGURES

INTRODUCTION

In this third quarterly period of the contract, principal effort was in the fabrication of the calorimeter and deliverable breadboard.

Tests were completed on most power modules, and in-process tests conducted on printed circuit boards for Control Module. Preliminary test was made of the 2 KW Screen Staggered-Phase System.

Subsystem tests were conducted, using deliverable modules, on the Low Voltage Subsystem, the Accelerator Subsystem, and the Arc Subsystem.

Tests were conducted on a new power transistor, Transitron ST18037, a possible substitute for Solitron 8805, promising an improvement of 1% in efficiency.

1.0 MODULE TESTS

The following module tests were conducted in this period:

a) 5 KHz Line Regulator - Problems Resolved - Current limiting was added to this module, since it was determined that fuse would not protect line regulator from shorts in 5 KHz inverter, thereby inhibiting operation of the standby inverter. Test verified ability of the line regulator, as modified, to safely blow the inverter fuse.

b) Accelerator Line Regulator - No Problems - Same comments as (a) above.

c) 5KHz Inverter (Prime and Standby) - Test OK.

d) Accelerator Inverter (Prime and Standby) - Test OK.

e) Magnetic Modulator (Vaporizer, Neutralizer Heater, Neutralizer Keeper, and Magnet Supplies) - Faulty Magnet mag-amp replaced.

f) Arc Inverter (Prime and Standby) - Test OK

g) Arc Rectifier Filter - Test OK

h) Cathode Inverter (Prime and Standby) - Partially tested.

i) Screen Inverter - Eight Modules - Tests of eight (8) completed inverter modules disclosed that variations between Solitron SDT8805 power transistors in base-emitter voltage, combined with poor switching times reported on earlier, resulted in higher switching losses than tolerable (total transistor losses of 14 watts at 300 watts load versus 8 watts design goal and 12 watts maximum allowable thermally). These tests also indicated the desirability of improving heat transfer between transistors and radiating area of the module plate.

As a result of the above tests, three (3) changes were initiated:

1) Increase base drive voltage from 2.5 volts and 1 amp to 4 volts and 1 amp, with increase of turn-on drive to 2 amps with "speed-up capacitor" (was $\approx$ 1.2 amps).

2) Decrease the operating frequency from 12.5 KHz to 10.0 KHz.

3) Improve heat transfer.

From the above, the base drive power will increase from approximately 3 watts (including turn-off) to approximately 5 watts. However, it has been verified that the increase of 2 watts in base drive is more than compensated by a reduction of 6 watts in collector losses. The expected total collector and base drive losses will thus be approximately 13 watts versus the design goal of 11 watts or a loss of 2/3% in efficiency at 300 watts out (inverter total losses expected $\approx$ 22 watts, or an efficiency of $\frac{300}{322} \sim 93\%$). The above change in base drive required replacing two drive transformers per inverter. This was done and all modules retested with new transformers.

Heat transfer improvement was required in two (2) areas: (a) transistor mounting insulation, and (b) chassis heat transfer.

The mounting technique first used was a 2 mil Kapton washer front and back. This technique was used as a temporary method pending evaluation, in vacuum, of other techniques. This evaluation has now been completed, and the results are indicated in the attached graph, Figure 1-1. Accordingly, we used the technique of insulating with a .060" beryllium oxide washer, with .010" indium foil between washer and transistor, RTV 11 between washer and chassis, nylon bushing in hole (no shoulder), and nut insulated with mica washer. As the graph indicates, a drop of 1 to 2°C may be expected with 4 watts per transistor, in vacuum.

The other change incorporated was to improve heat transfer of the module radiator. The magnesium alloy used, AZ318F, most readily available for the breadboard, has roughly 2/3 the thermal conductivity of the best material, ZK60A-TS. To offset the low thermal conductivity, and further improve the heat transfer, a 2" diameter, .060" thick, pure magnesium washer was bonded to the nut side of the module plate. This is expected to reduce the present thermal gradient between transistor mounting area to center of plate from 5°C to 2°C.

The decision to change the operating frequency from 12.5 KHz to 10.0 KHz was made after a careful review of output transformer designs. Since original design was for flux density 1400 Gauss at 12.5 KHz, at 10 KHz, density will be 1750 Gauss, or half the allowable flux density of 4000 Gauss at 75°C and 4 Oersteds (1 ampere exciting current). Core losses will increase from 28 mw/cm^3 to 37 mw/cm^3. With a core volume of 31.5 cm^3, core loss will increase from 0.88 watts to 1.16 watts or an increase of 0.28 watts. Since transistor switching losses will be approximately 4 watts at 10 KHz versus 5 watts at 12.5 KHz, a savings of 1-0.28 = 0.72 watts will result, with the additional advantage of a lower temperature rise in transistors.

In this period, information was received from Transitron Corporation on a 20 amp, 400 volt transistor indicating that this should be substantially more efficient, and more reliable than the Solitron device now used. Switching speeds, at 8 amps, between 0.5 and 0.8 microseconds, were expected, with high resistance to secondary breakdown indicated by a permissible inductive switching envelope. Also, a positive temperature coefficient on beta at 8 amps is guaranteed, a much more reliable characteristics than the negative coefficient of the Solitron device.

Samples of the Transitron device were tested to verify characteristics. Results are given below:

Two (2) sample Transitron transistors, Type ST18037, were received and tested. The tests verified the expected improvement in switching time and collector voltage V_{ceo}, relative to the Solitron 8805. Following is the test data obtained.

TABLE 1

Serial No.	T_{Stor}	T_{Delay}	T_{Rise}	T_{Fall}	BV_{ceo}	$V_{cesat(10A)}$
ST18037 Spec	1.0	----	.8 μs	.8 μs	400	1.0
M17865	2.5	.04 μs	.4 μs	.7 μs	400	.322
M17868	2.5	.03 μs	.5 μs	.45μs	400	.249
Solitron 8805 (Typical)	4.0	?	1.2μs	.8 μs	300	.44 (6A)

It will be noted that storage time is longer (2.5 μs) than specification of 1.0 μs. This is tolerable, however. Switching times are appreciably better than specification, as is V_{cesat}. If samples are typical, a gain of 1% in system efficiency should result from improvements in both switching times and V_{cesat}. Also, higher V_{ceo} will result in substantially more margin and reliability, relative to expected stress of 200 volts transient, worst case.

Since switching losses are proportional to the sum of rise and fall times, a significant improvement is expected here, since with the worst of two samples, the sum of 1.1 μs compares with 1.9 μs of the best 10% of Solitron units. Similarly, the best 10% of Solitron units show a V_{cesat} of .43 volts at only 6 amps versus 0.322 at 10 amps for the Transitron units, so an appreciable improvement may be expected in this area.

j) <u>High Voltage Filter</u> - No problems.

k) <u>Control Module</u> - This module consists of seven (7) printed circuit cards and two (2) discrete component panels. At the time of this report, the roll-off circuits and function generator have been tested in the completed cards. Data is shown in Figures 1-2 to 1-5.

The roll-off control characteristics exhibit a more rounded knee than expected. However, this should not result in any difficulty in the engine control loop. If the curvature is considered objectionable by JPL, it may be minimized by saturating the control modulators below 5 volts, say at 4.5 volts, for the vaporizer and neutralizer heater systems, since the maximum current is not specified as being closely regulated. However, the cathode control roll-off will be sharp since, unlike the vaporizer and neutralizer heaters, 40 amps is obtained at 0 volts control, and cut-off at 5 volts.

2.0 SUBSYSTEM TESTS

a) "Low-Voltage" Subsystem - This consists of the 5 KHz Line Regulator, the 5 KHz Inverter and Standby, and the Magnetic Modulator modules. The system was tested using simulated control (roll-off) with line varying from 40 to 80 volts, and normal loads to shorts. Telemetry outputs and control sensitivity were recorded. Results are shown in Figures 2-1 to 2-7.

b) Accelerator Subsystem - This consists of the Accelerator Line Regulator, the Accelerator Inverter and Standby, and the High Voltage Filter. System was tested with line from 40 to 80 volts and load from zero to 100 ma. Regulation with line was less than 1%. Regulation with load was as follows:

LOAD	OUTPUT	
1 ma	2291 volts	
1.5 ma	2170 volts	
6.0 ma	2016 volts	Spec = 1% for 5 to 10 ma
9.8 ma	2002 volts	≐ 20 volts allowable
13.8 ma	1997 volts	
24 ma	1986 volts	
48 ma	1960 volts	
98.5 ma	1867 volts	

c) Arc Supply Subsystem - This system consists of the Arc Inverter and Standby, and the Arc-Rectifier Filter modules. System was tested for regulation and telemetry with line from 40 to 80 volts and load from 0 to 7 amps. Performance was satisfactory. Data is shown on Figures 2-8, 2-9, and 2-10. Linearity of current sense was very good, showed no sensitivity to line voltage, and should provide a good input to control module cathode control.

d) Screen Subsystem - An important test conducted in this period was that of the staggered-phase screen system. These tests were conducted from no load to 0.6 ampere at 2 KV out, with line varied from 40 to 80 volts, in a closed loop voltage-regulating mode, using deliverable inverter modules, high voltage filter, and breadboard staggered-phase drive.

The test was limited to 0.6 ampere maximum, pending replacement of inverter drive transformers for increased base drive to tolerate slow switching speeds of Solitron transistors.

Good regulation of output voltage was obtained, showing less than 1% regulation from 40 to 80 volts line at loads from 0.2 to 0.6 ampere, with ripple less than 100 volts peak-to-peak (2½% peak versus 5% spec). At no-load, average value was still close to 2 KV, with 500 volts peak-to-peak ripple due to limit-cycling mode. This peak voltage, no-load, will be less than 2500 volts, considered acceptable by JPL.

The test of the staggered-phase system included measurement of the signal-to-noise ratio on the inverter input gates. This showed about ½ volt ripple on the 5 volt signal, an acceptable value. However, the system tested was then modified to provide buffering between phase-shifting shift register and inverter input gates, since direct-coupling between register and gates could result in a failure of the register with a shorted inverter gate, not tolerable for inverter redundancy. Therefore, buffering was added and system retested with no difficulties.

New screen-drive transformers were then added.

All power transistor mountings were also converted to beryllium-oxide, indium type, with additional 2" diameter, .060" thick magnesium washer added under nut to increase chassis conductivity.

A worst-case analysis of capacitor coupling used between first and second stage DTL 932 gates in PWM inverters (Screen, Cathode, and Arc) revealed that for very narrow pulses, such as demanded at no-load, the capacitor coupling at low temperature extremes would result in ratcheting of the inverters to turn-on sooner than desired, and improper operation at no-load (excessive output). Consequently, it was decided to remove the AC coupling from PWM inverters and protect against latch-up in counter or shift register by an AC detection circuit to shut system down rapidly in the event of latch-up, thus avoiding a catastrophic failure of PWM inverter drivers, if latch-up occurred in test phase due to wiring error or test-induced failures.

Further consideration of the hazards associated with testing indicated that with inverter gates directly coupled to counter or shift register, without a pull-down resistor on input gates, an inadvertent opening of the connector at the LV Connection Module could result in all inverter input gates going to "1" state and probable burn-out of inverter driver transistors, with AC capacitor coupling removed from PWM inverters as indicated above. It was also apparent that any failure of an inverter driver transistor which resulted in an open emitter (low probability, but possible) could result in 35 volts carrying through gates to counter or shift-register, and catastrophic failure of the latter.

In view of the above considerations, it was decided to diode couple all inverter inputs, to block possible 35 volts, and add a 500 ohm pull-down resistor at all gate inputs, to hold inputs at "0" state with an open line. Both these additions slightly reduce noise immunity, but are a desirable trade-off.

The above-indicated changes have been breadboarded and tested, and have been incorporated in the fabrication of deliverable modules. System is now ready for retest with these changes.

The increased base drive now available will permit next test to be conducted at loads up to 1 ampere.

3.0 TEST CONSOLE FABRICATION

Figure 3-1 is a photograph of completed Test Console No. 2. This unit has been modified relative to Test Console No. 1, delivered on 1 December for use with the Breadboard of Contract 952229. Modification was necessary to provide for differences in inverter modules (number of inverters and standby packaging), also for heavier line current required at 40 volts in new system relative to 80 volts in earlier system.

4.0 CALORIMETER FABRICATION

Figures 4-1 and 4-2 are photographs of completed calorimeter. The system has been pressure tested and verified as okay in this test. It is now being prepared for thermal calibration, which should be completed by 1 May, ready for test of deliverable breadboard.

5.0 BREADBOARD FABRICATION

Figures 5-1 to 5-14 are photographs of the power conditioning assembly and modules. As may be seen from the photographs, fabrication of all modules is complete except for control module, which is shown in a state of partial completion prior to final assembly, and low voltage connection module, containing staggered-phase system, which is in board assembly state, not shown.

6.0 MILESTONE SCHEDULE

Figure 6-1 is a chart of milestones reflecting change in schedule to incorporate changes of proposed TDM No. 10, currently being negotiated.

SOLID LINE: IS VACCUM 1.2×10^{-4} TO $6. \times 10^{-5}$ TORR
ALL OTHER LINE AMBIENT PRESSURE

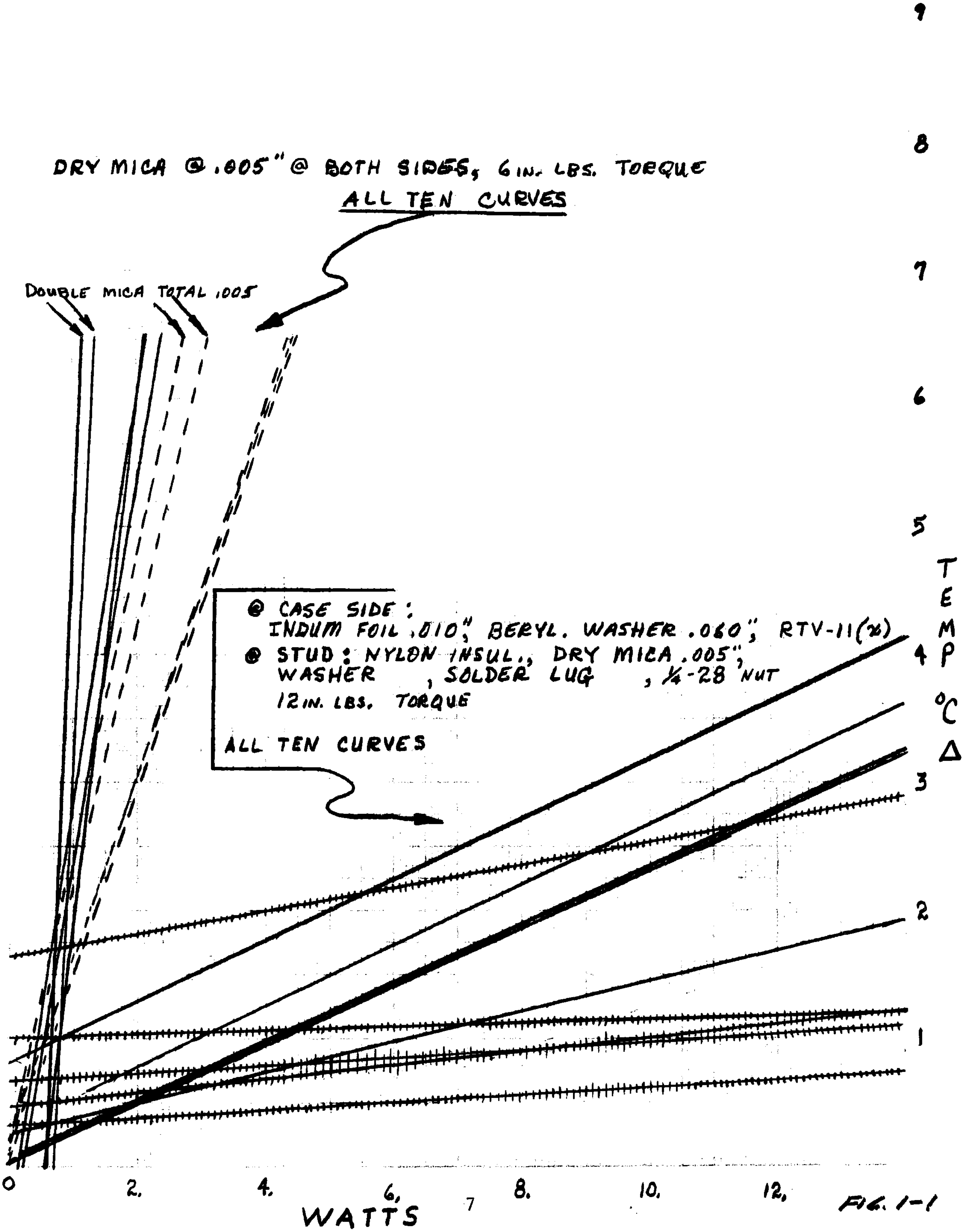
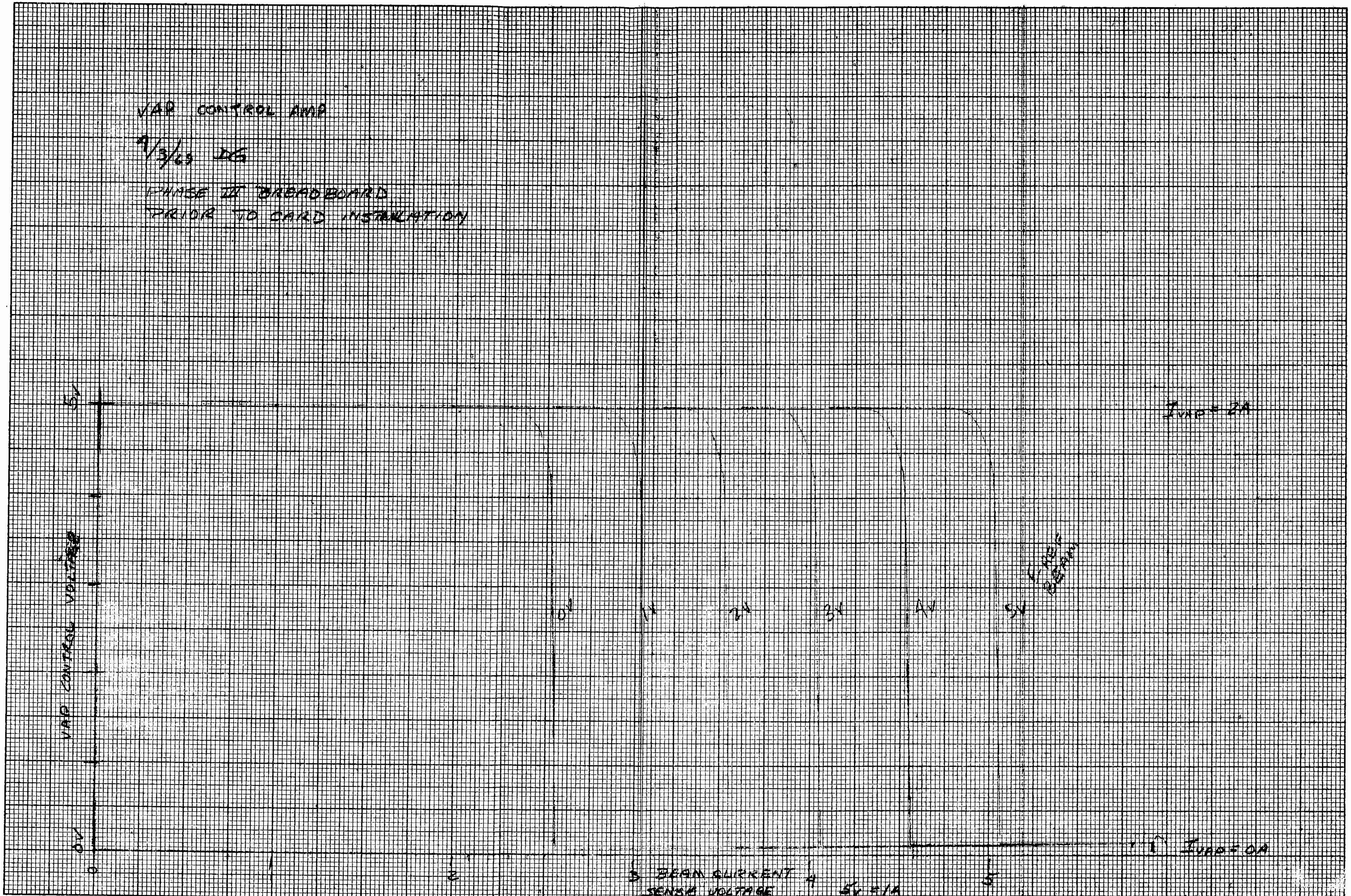


FIG. 1-1



VAR CONTROL AMP
9/3/69 DG
PHASE II BREADBOARD
PRIOR TO CARD INSTALLATION
VAR CONTROL VOLTAGE
5V
0V
0
1
2
3
4
5
BEAM CURRENT SENSE VOLTAGE 5V = 1A
0V
1V
2V
3V
4V
5V
I REF BEAM
I_{VAP} = 2A
I_{VAP} = 0A

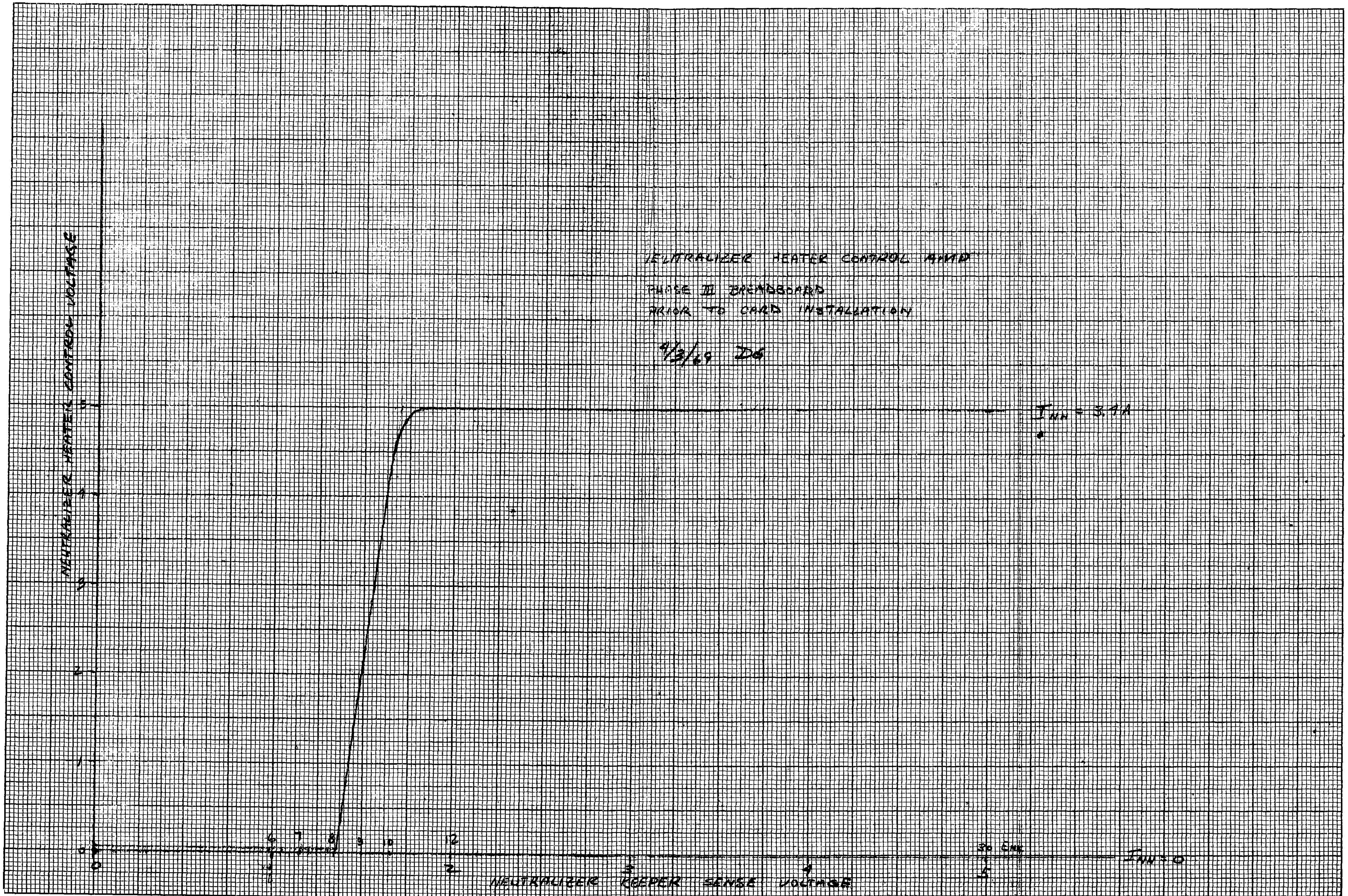
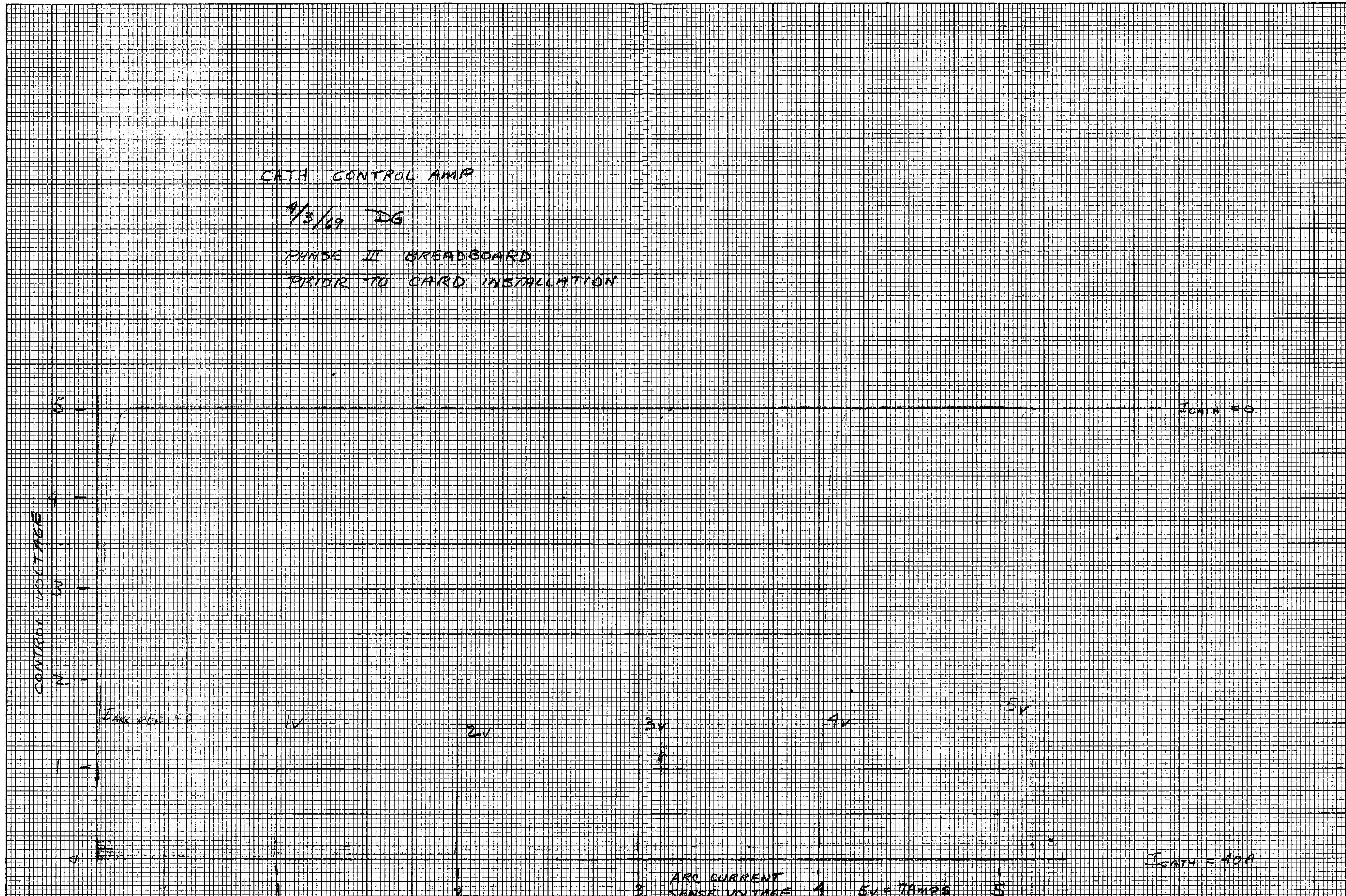

NEUTRALIZER HEATER CONTROL AMP
PHASE III BREADBOARD
PRIOR TO CARD INSTALLATION
4/3/69 DG
I_{NH} = 3.7A
I_{NH} = 0
NEUTRALIZER HEATER CONTROL VOLTAGE
NEUTRALIZER KEEPER SENSE VOLTAGE
0
1
2
3
4
5
6
7
8
9
10
12
30 CM

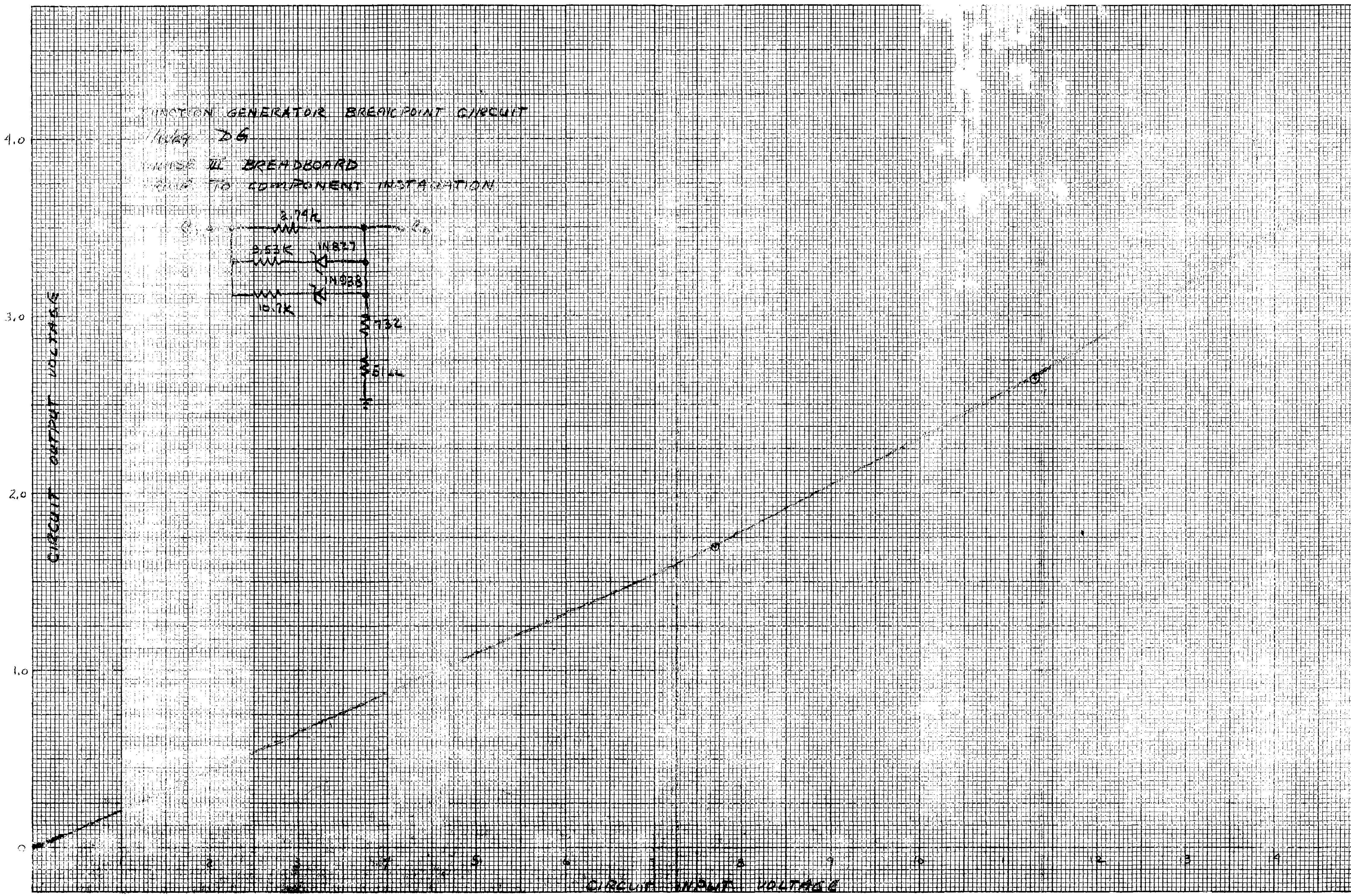
FIG 1-3



CATH CONTROL AMP
4/3/69 DG
PHASE III BREADBOARD
PRIOR TO CARD INSTALLATION
CONTROL VOLTAGE
5
4
3
2
1
$I_{CATH} = 0$
$I_{CATH} = 40A$
1V
2V
3V
4V
5V
1
2
3
4
5
ARC CURRENT
SENSE VOLTAGE
5V = 7AMPS

FIG 1-4

4



FUNCTION GENERATOR BREAKPOINT CIRCUIT
DG
PHASE III BREADBOARD
PRIOR TO COMPONENT INSTALLATION
2.74K
8.53K
10.7K
1N827
1N938
732
4.0
3.0
2.0
1.0
0
CIRCUIT OUTPUT VOLTAGE
2
3
4
5
6
7
8
9
10
12
CIRCUIT INPUT VOLTAGE

FIG 1-5

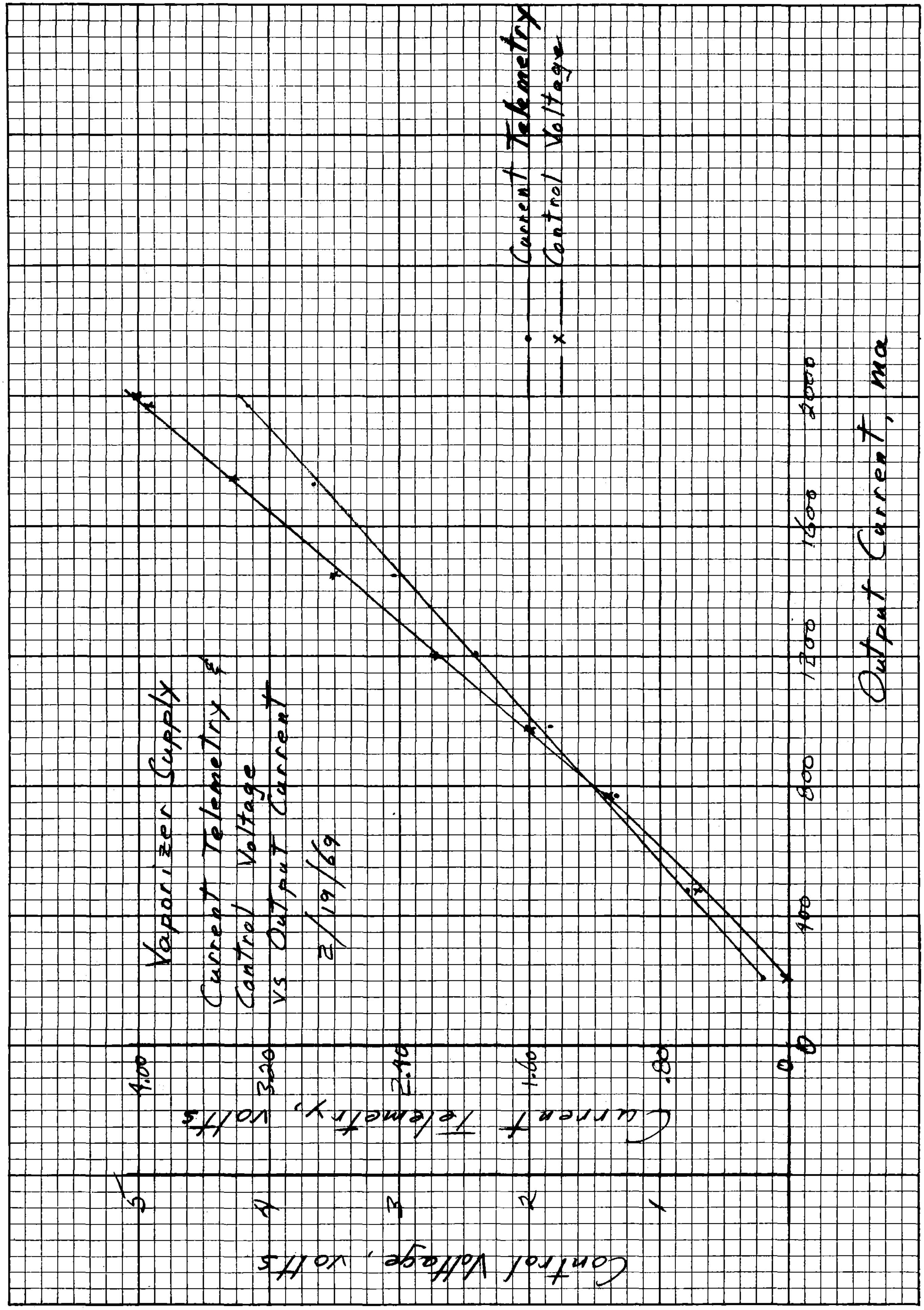

Vaporizer Supply
Current Telemetry &
Control Voltage
VS Output Current
2/19/69
Current Telemetry
Control Voltage
Output Current, ma
0
400
800
1200
1600
2000
Current Telemetry, volts
4.00
3.20
2.40
1.60
.80
0
Control Voltage, volts
5
4
3
2
1

FIG. 2-1

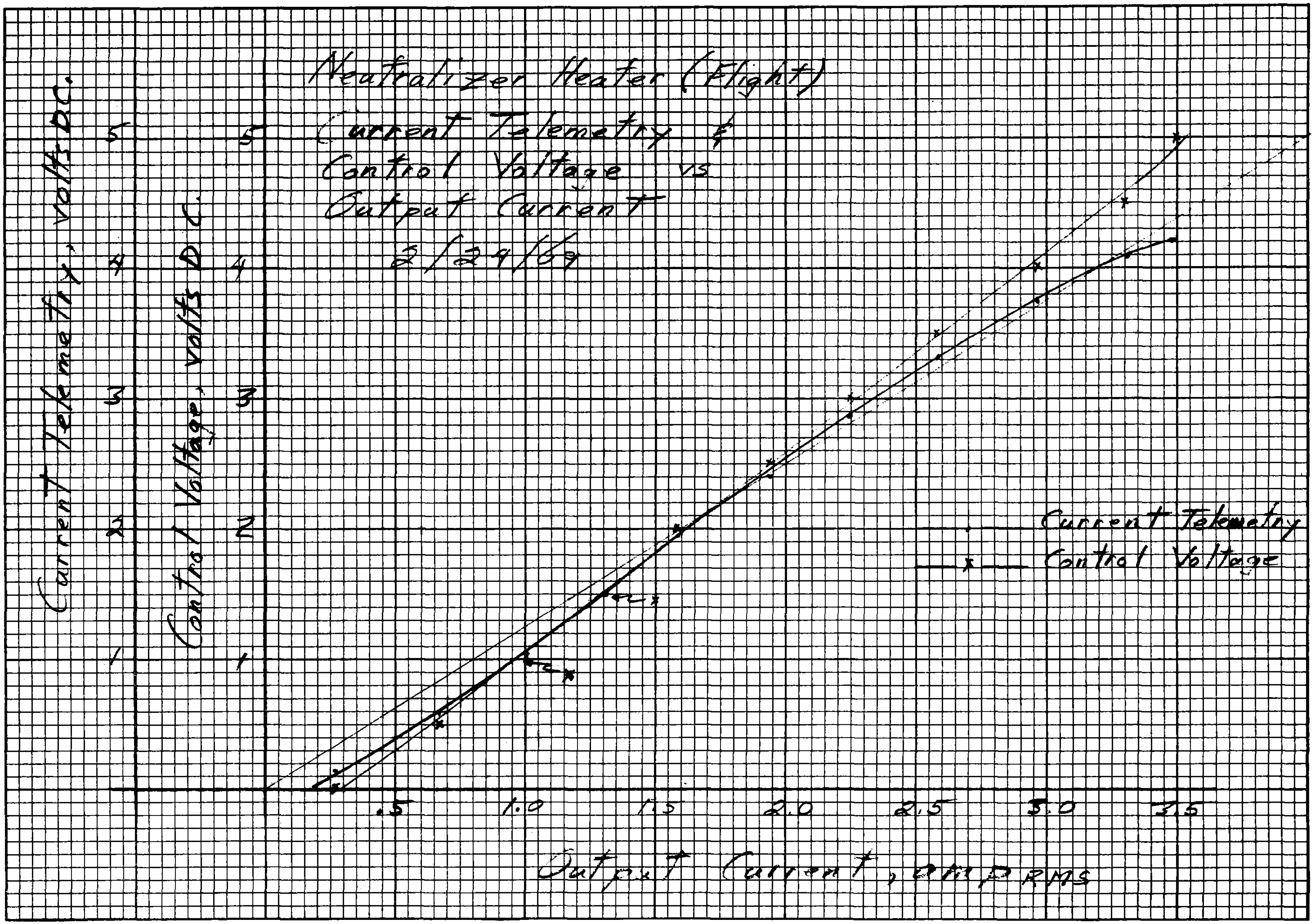

Neutralizer Heater (Flight)
Current Telemetry &
Control Voltage vs
Output Current
2/24/69
Current Telemetry
Control Voltage
Current Telemetry, volts DC.
Control Voltage, volts D.C.
Output Current, AMP RMS
1
2
3
4
5
.5
1.0
1.5
2.0
2.5
3.0
3.5

FIG. 2-2

K+E 10 X 10 TO THE INCH 7 X 10 INCHES 46 0703 MADE IN U.S.A. KEUFFEL & ESSER CO.

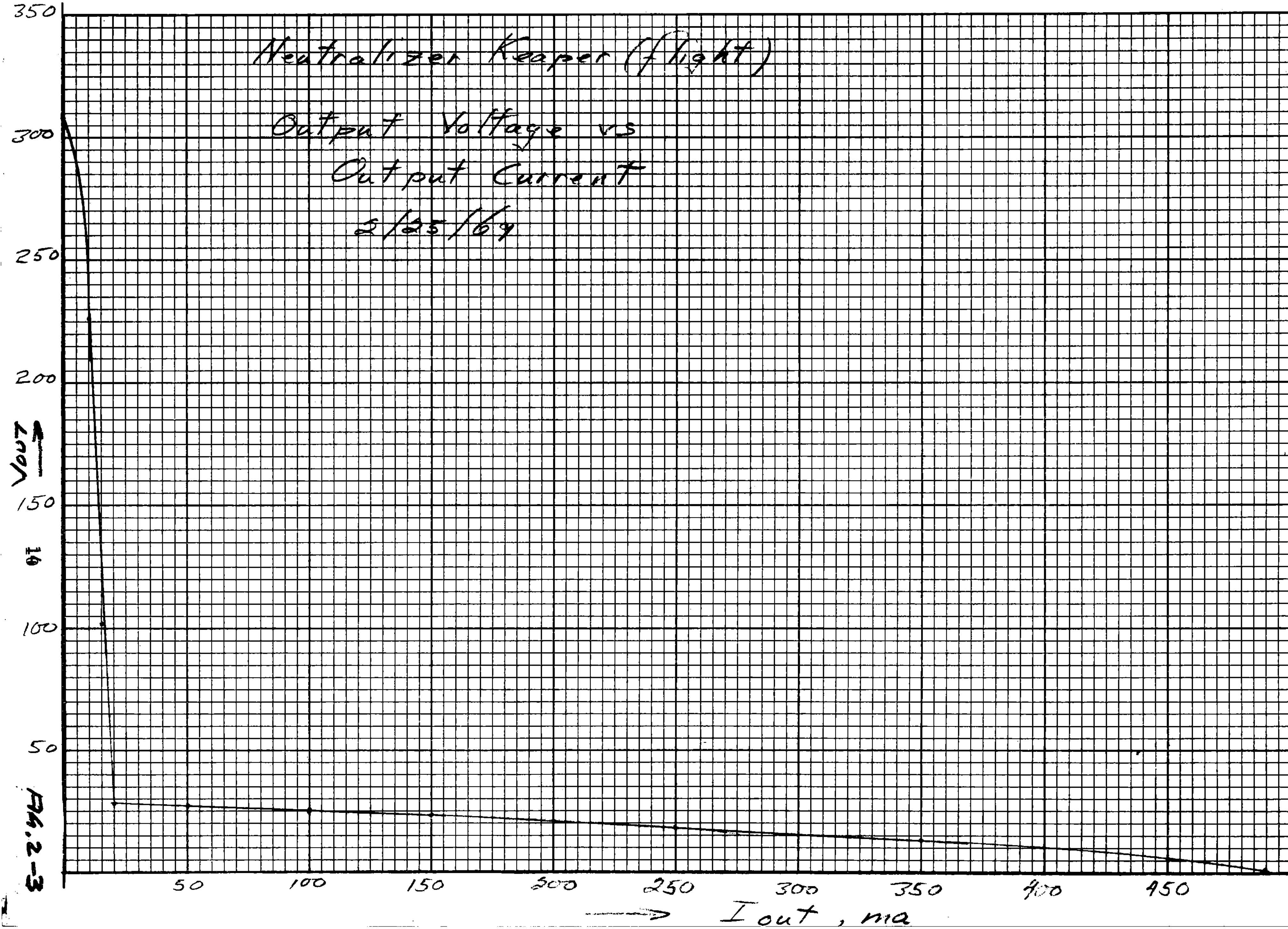


FIG. 2-3

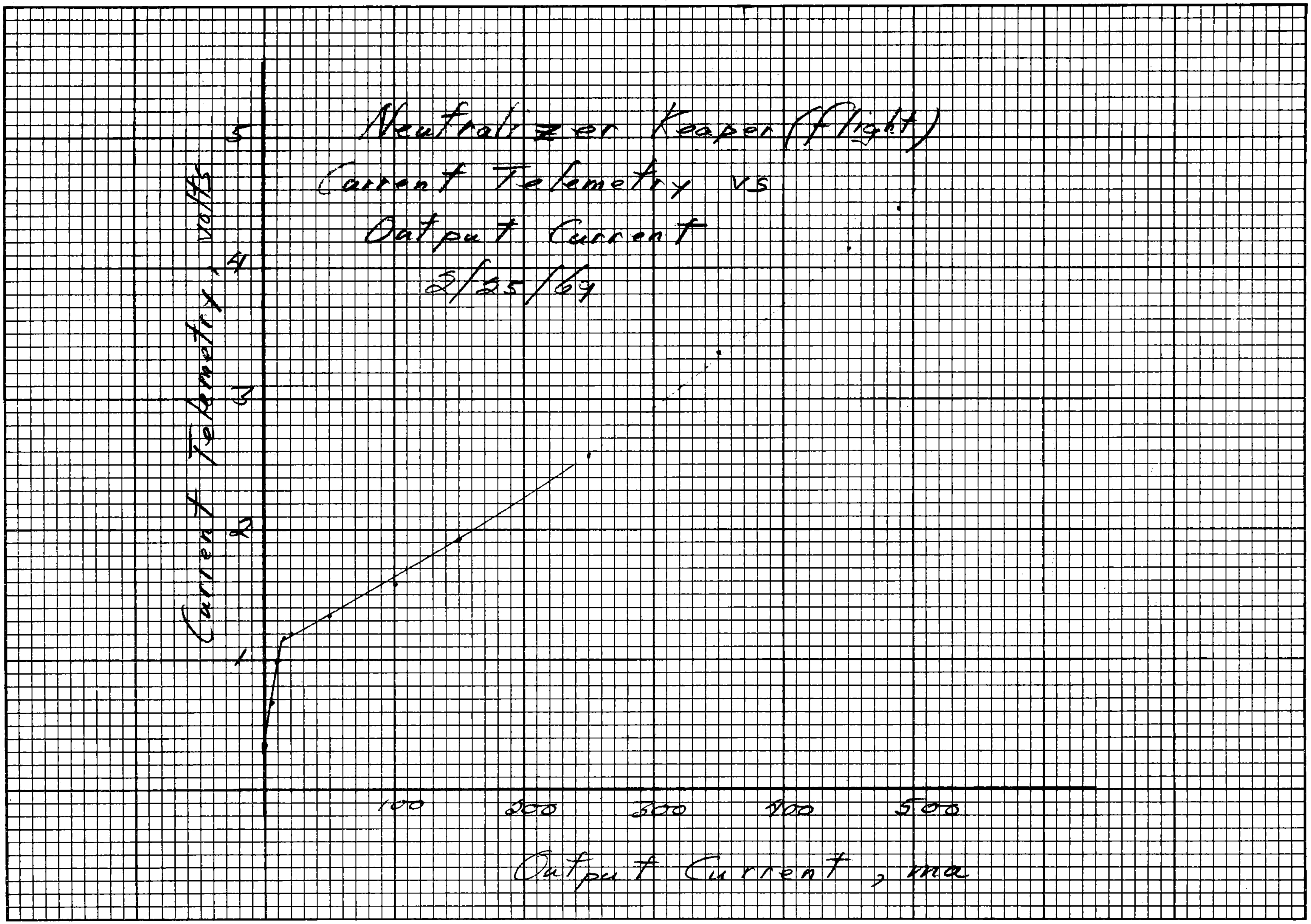

Neutralizer Keeper (flight)
Current Telemetry vs
Output Current
2/25/69
Current Telemetry, volts
1
2
3
4
5
100
200
300
400
500
Output Current, ma

FIG. 2-4

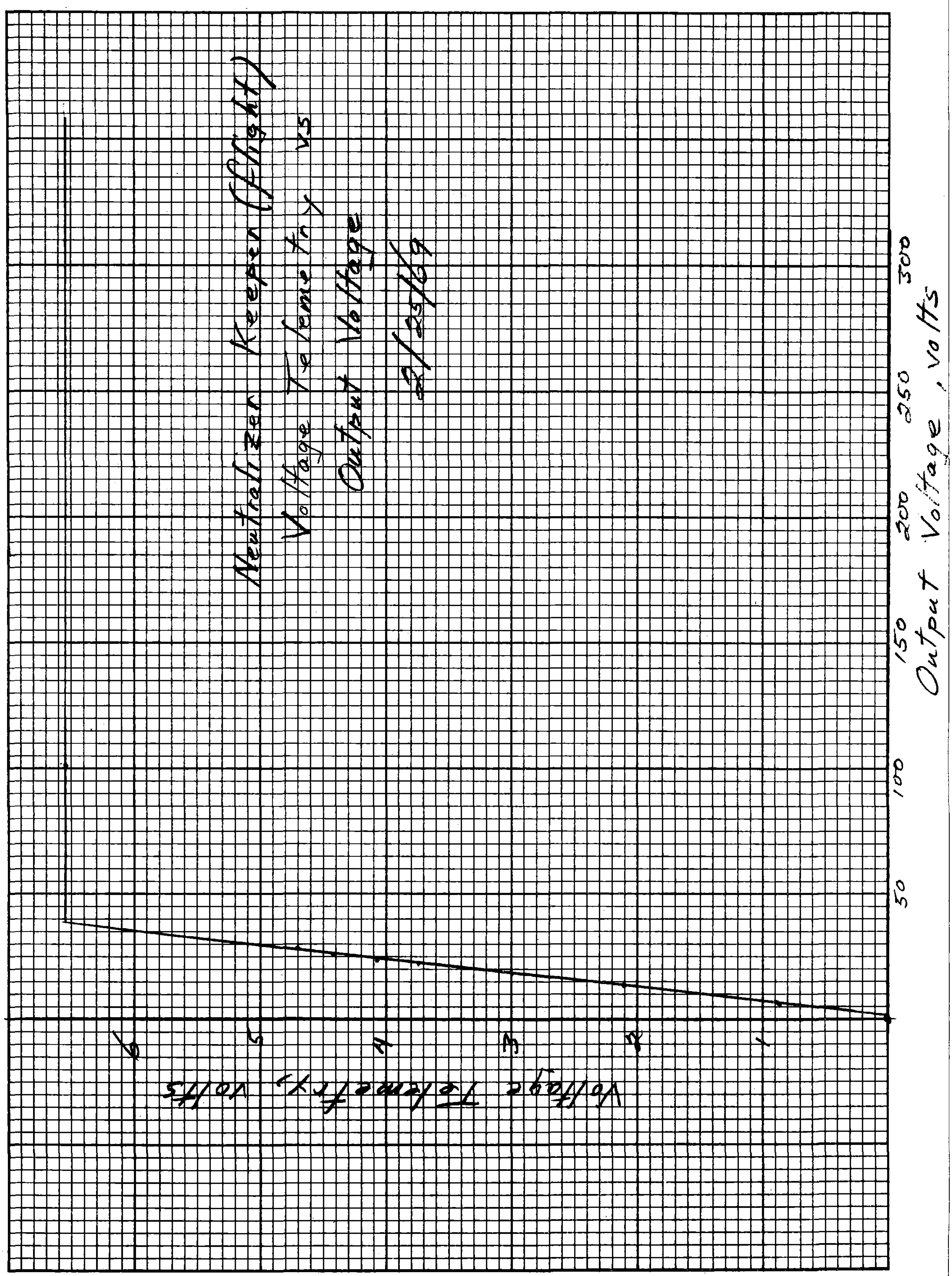

Neutralizer Keeper (Flight)
Voltage Telemetry vs
Output Voltage
2/25/69
50
100
150
200
250
300
Output Voltage, volts
1
2
3
4
5
6
Voltage Telemetry, volts

FIG. 2-5

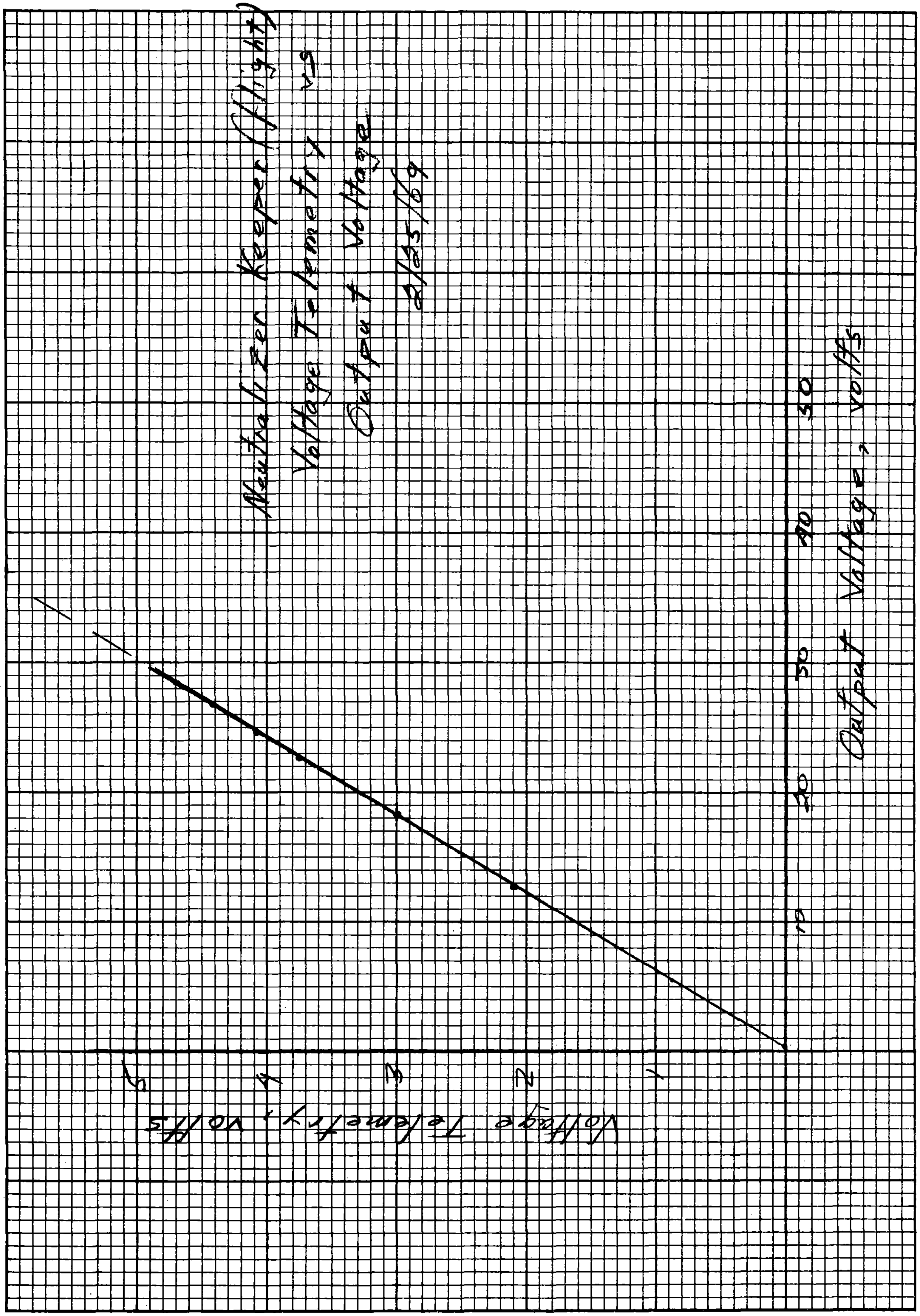

Neutralizer Keeper (flight)
Voltage Telemetry vs
Output Voltage
2/25/69
Output Voltage, volts
10
20
30
40
50
Voltage Telemetry, volts
1
2
3
4
5

FIG. 2-6

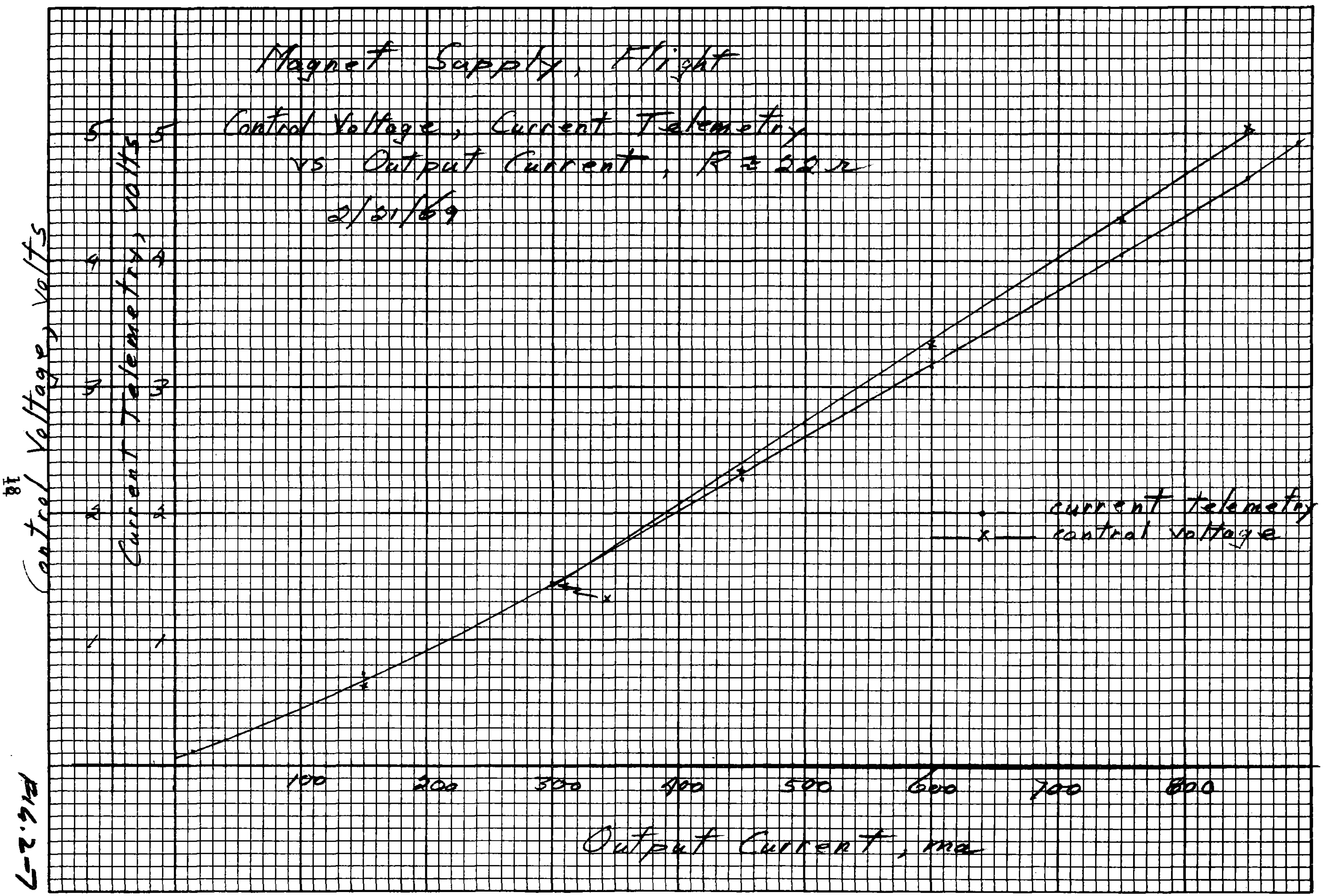
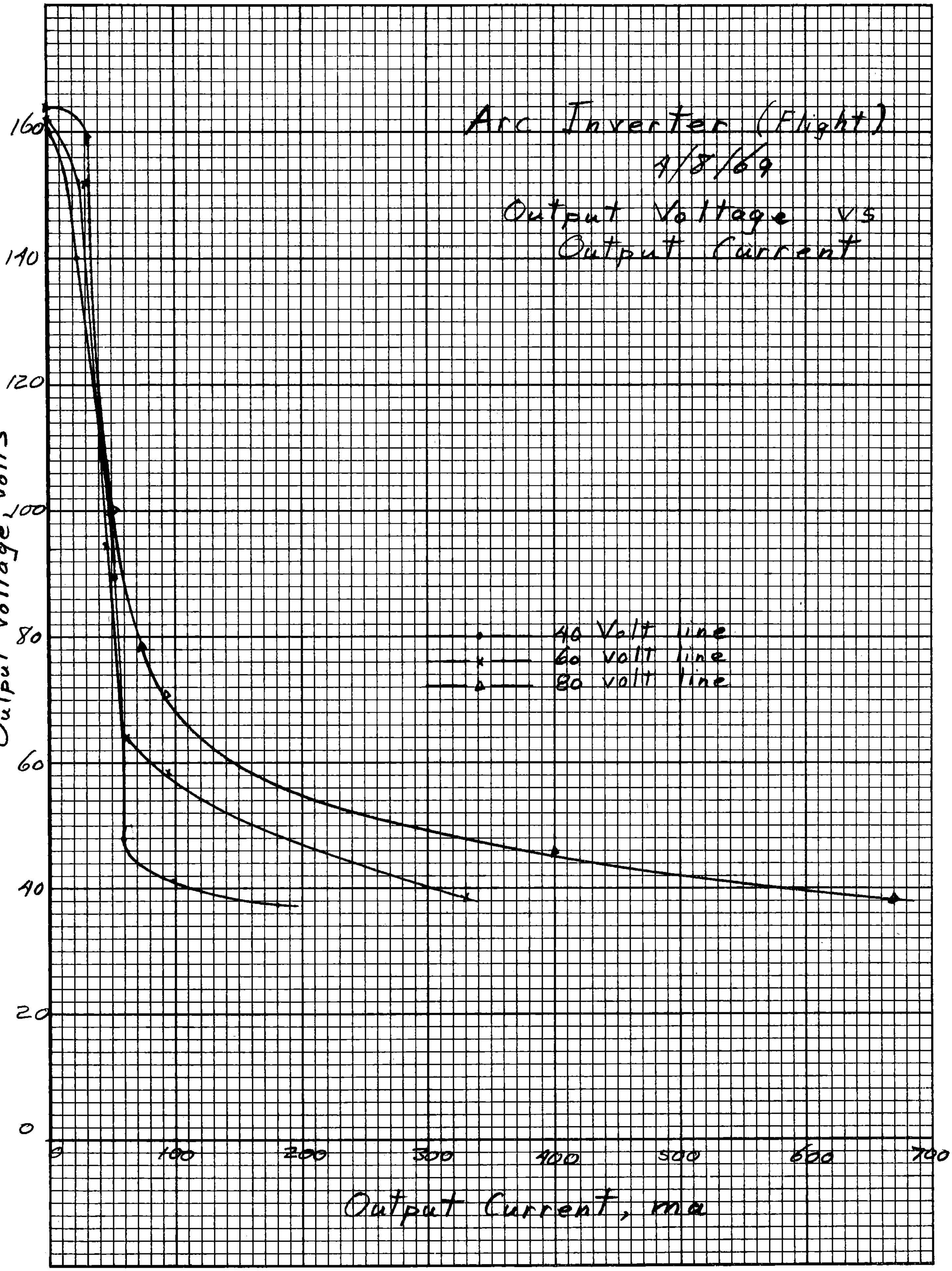

Magnet Supply, Flight
Control Voltage, Current Telemetry
vs Output Current, R = 22Ω
2/21/69
current telemetry
control voltage
Control Voltage, volts
Current Telemetry, volts
1
2
3
4
5
100
200
300
400
500
600
700
800
Output Current, ma

FIG. 2-7



Arc Inverter (Flight)
4/8/69
Output Voltage vs
Output Current
40 Volt line
60 volt line
80 volt line
Output Voltage, Volts
Output Current, ma
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
700

FIG. 2-8

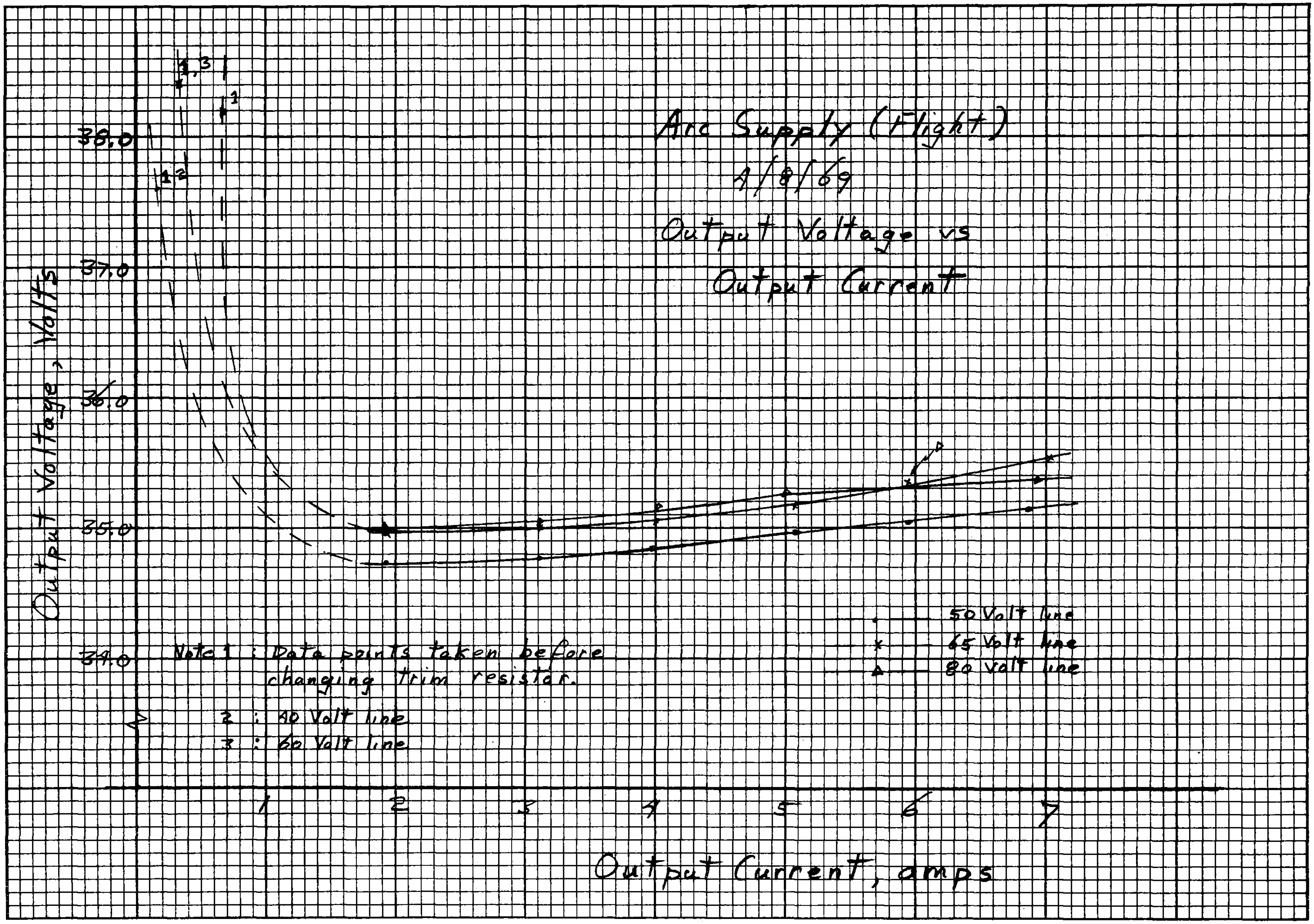

Arc Supply (Flight)
4/8/69
Output Voltage vs
Output Current
Output Voltage, Volts
38.0
37.0
36.0
35.0
34.0
1,3
1
1,2
1
2
3
4
5
6
7
Output Current, amps
50 Volt line
65 Volt line
80 Volt line
Note 1 : Data points taken before changing trim resistor.
2 : 40 Volt line
3 : 60 Volt line

FIG 2-9

Arc Supply
Current Telemetry vs Current Out
2/11/69

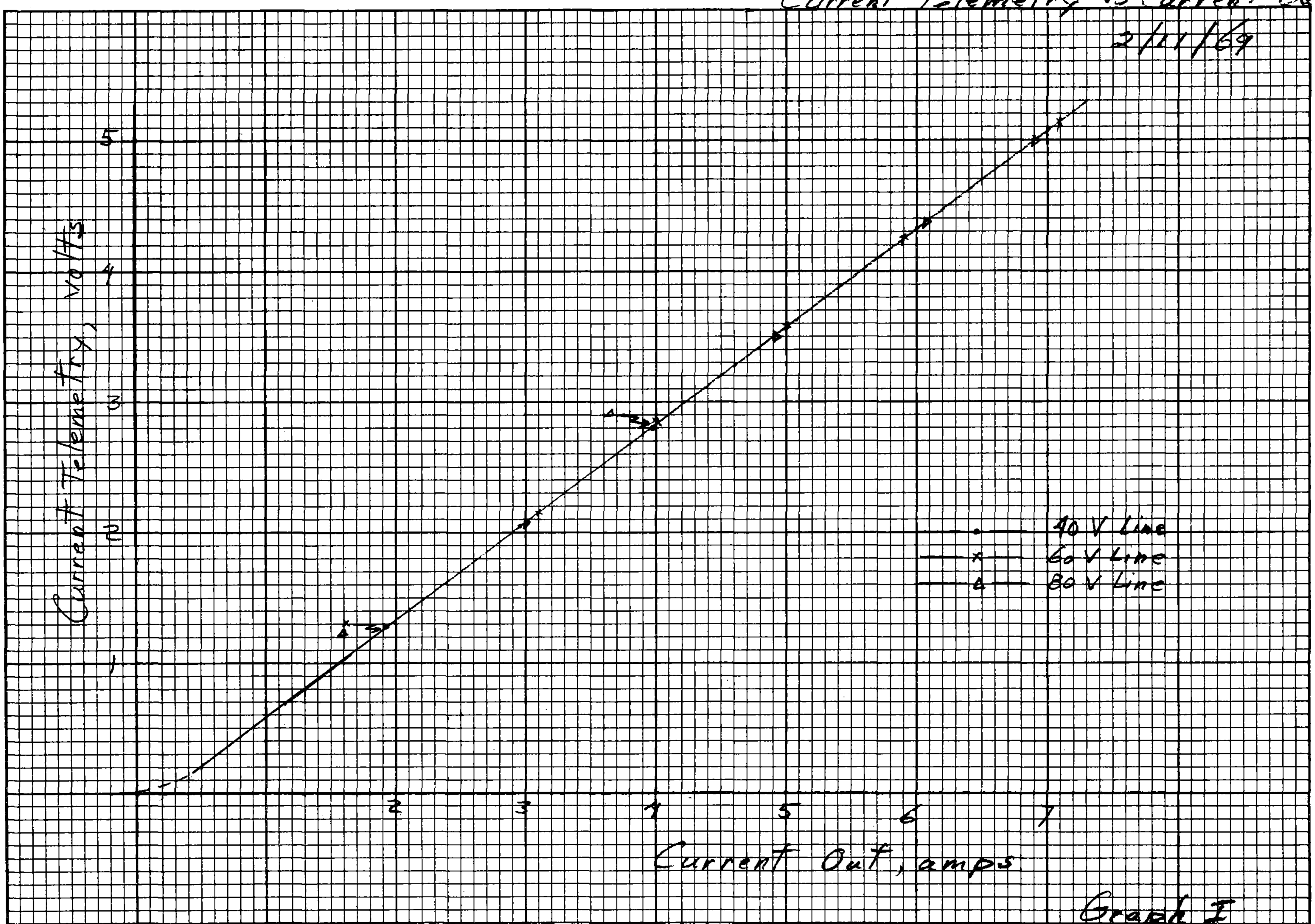


FIG 2-10

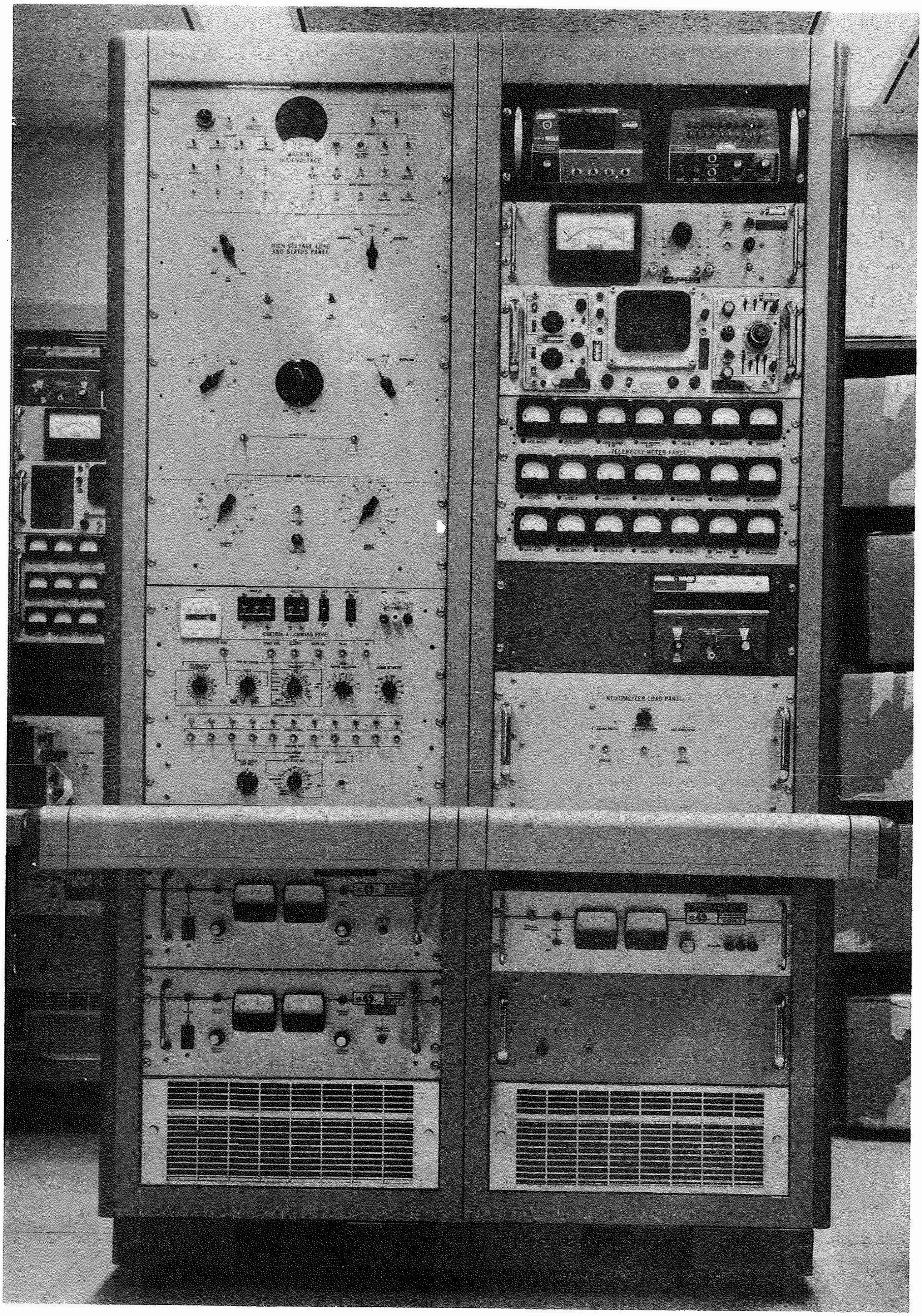


FIGURE 3-1 - Test Console

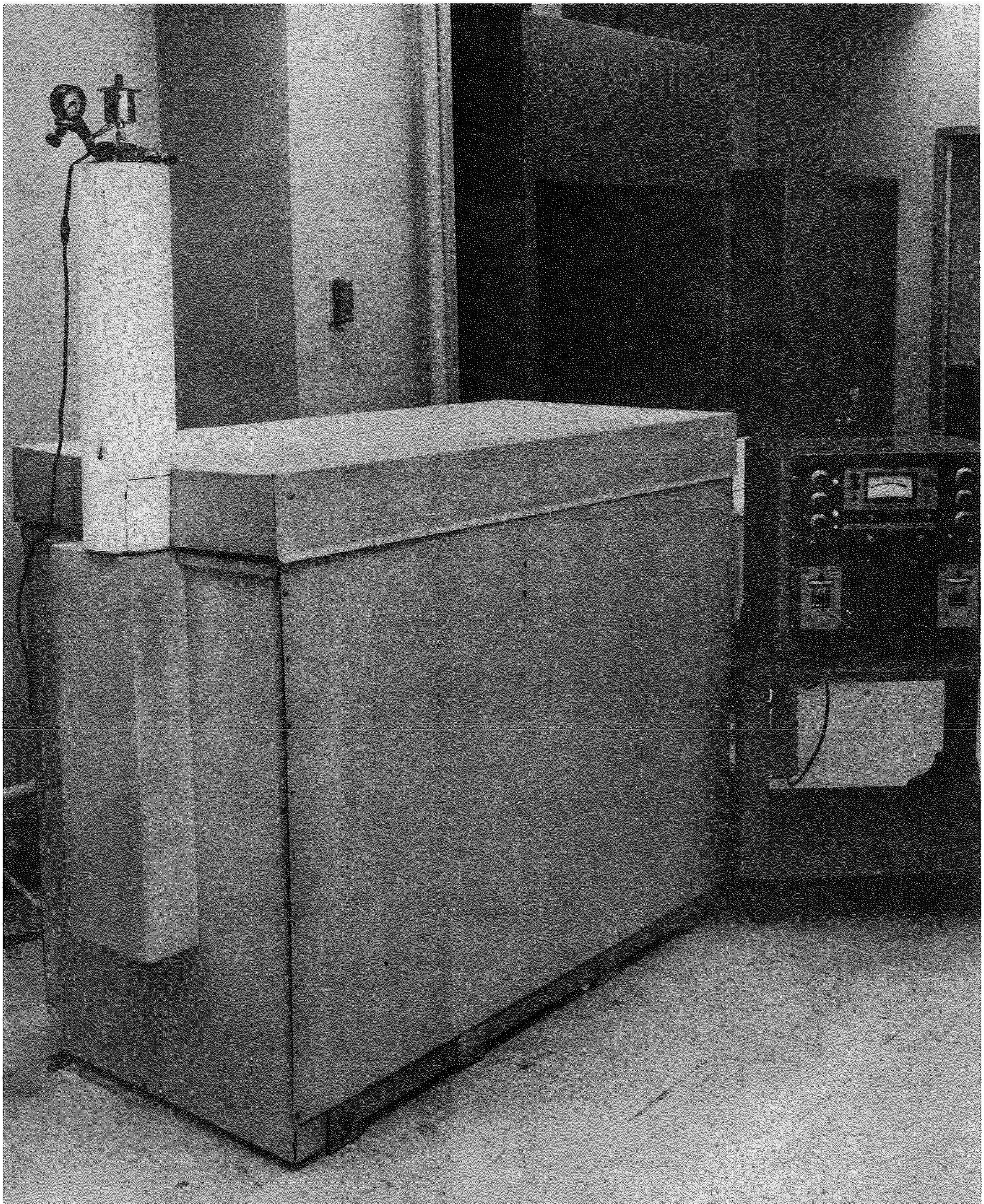


FIGURE 4-1 - Calorimeter

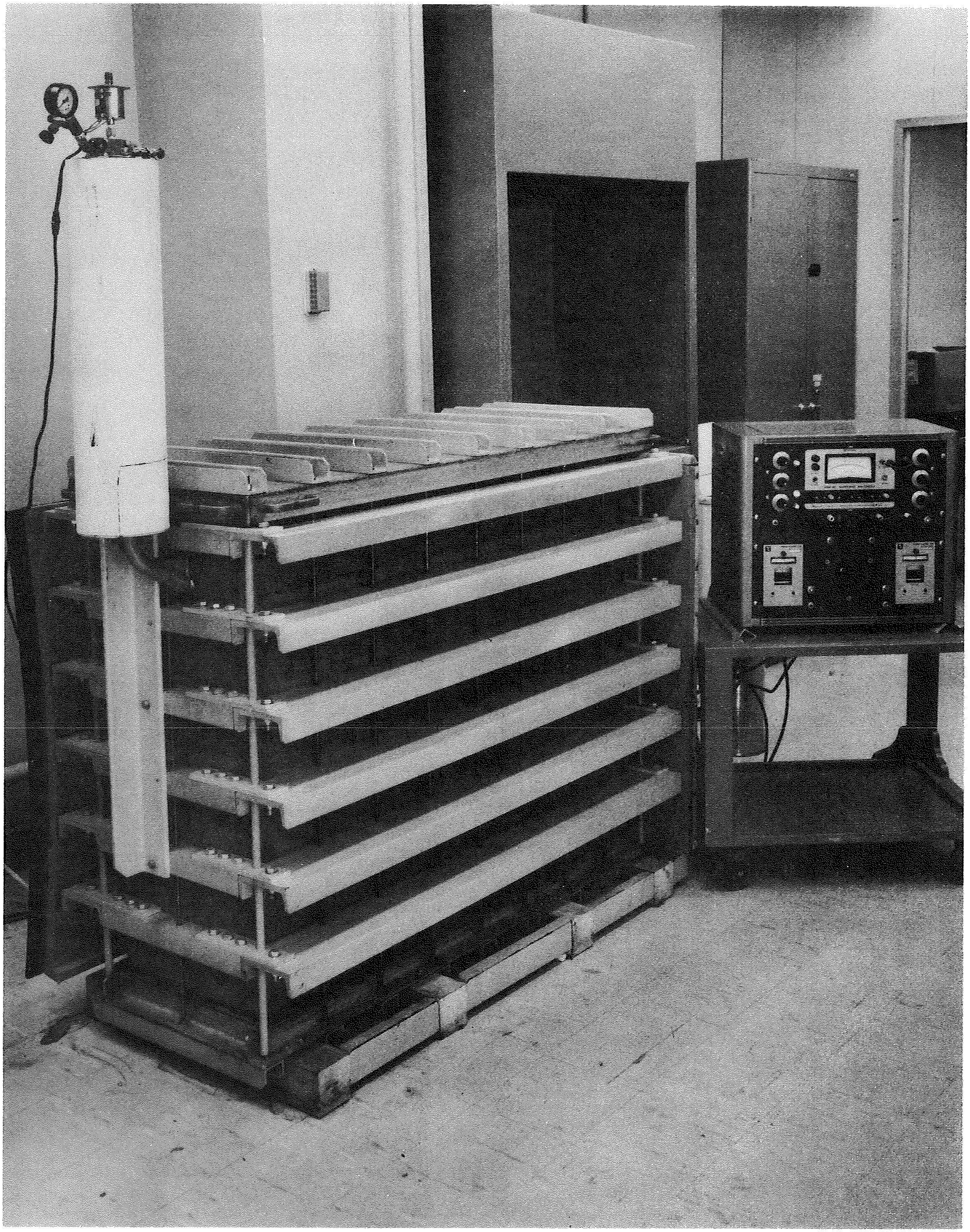


FIGURE 4-2 - Calorimeter

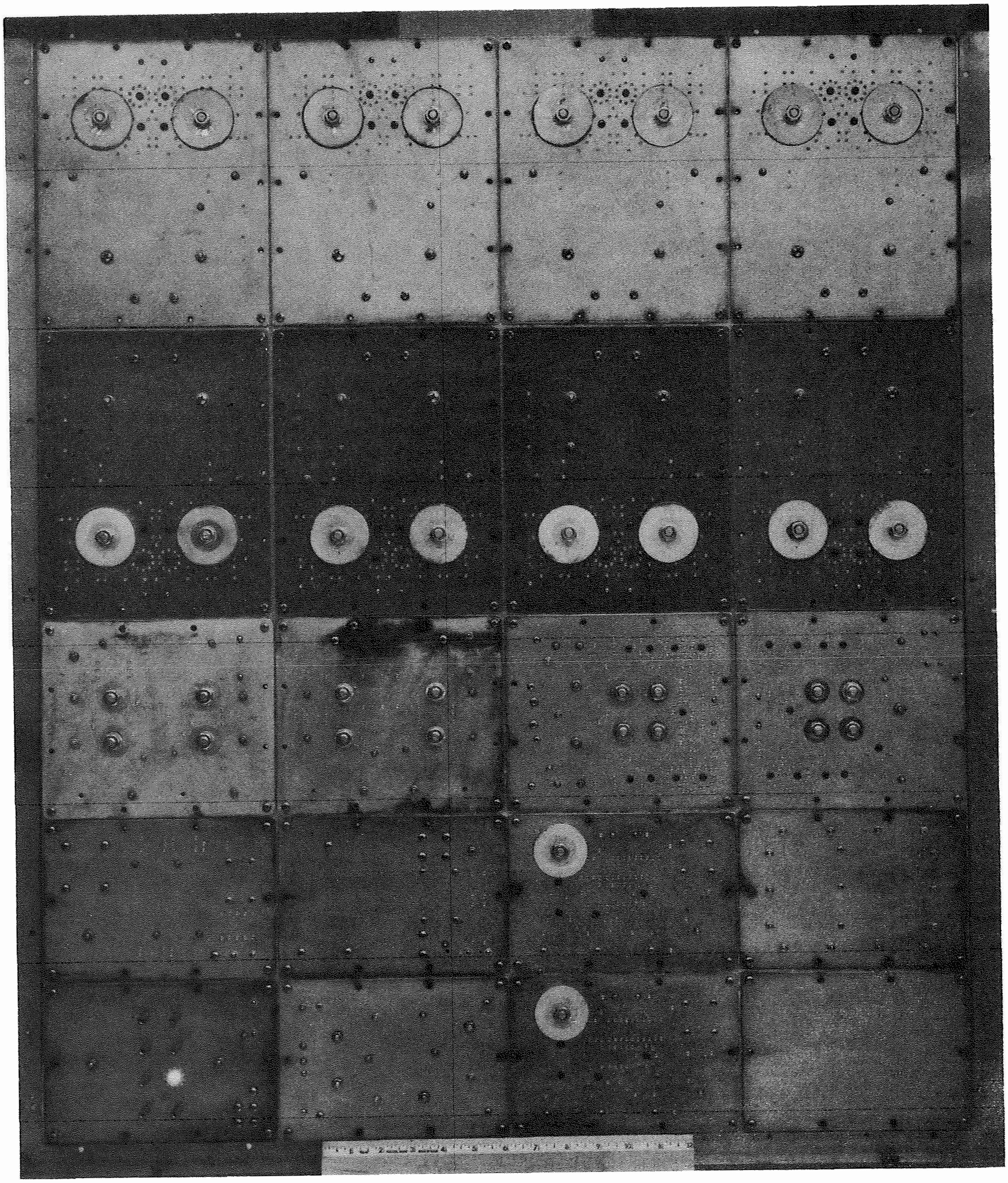


FIGURE 5-1 - Power Conditioning Assembly

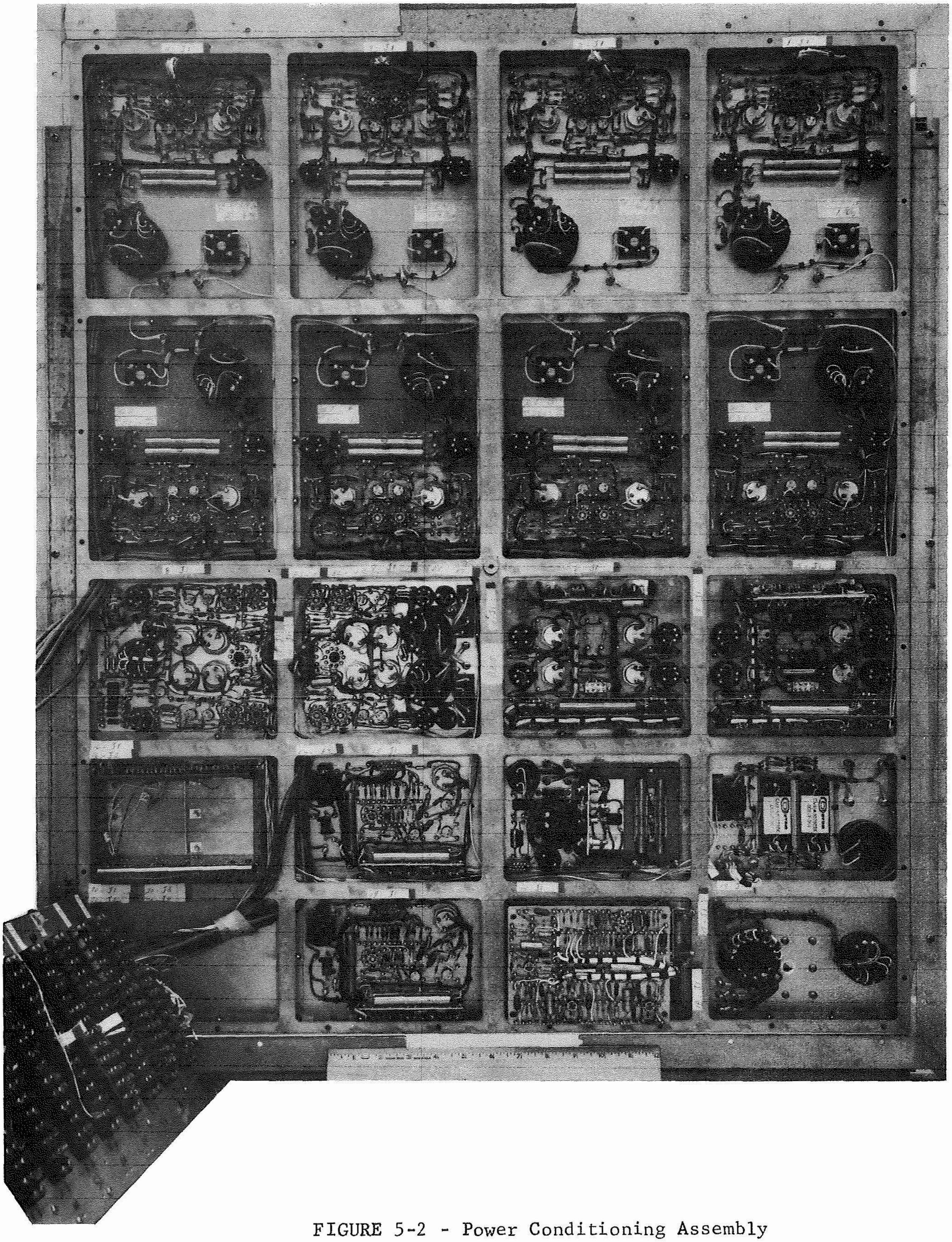


FIGURE 5-2 - Power Conditioning Assembly

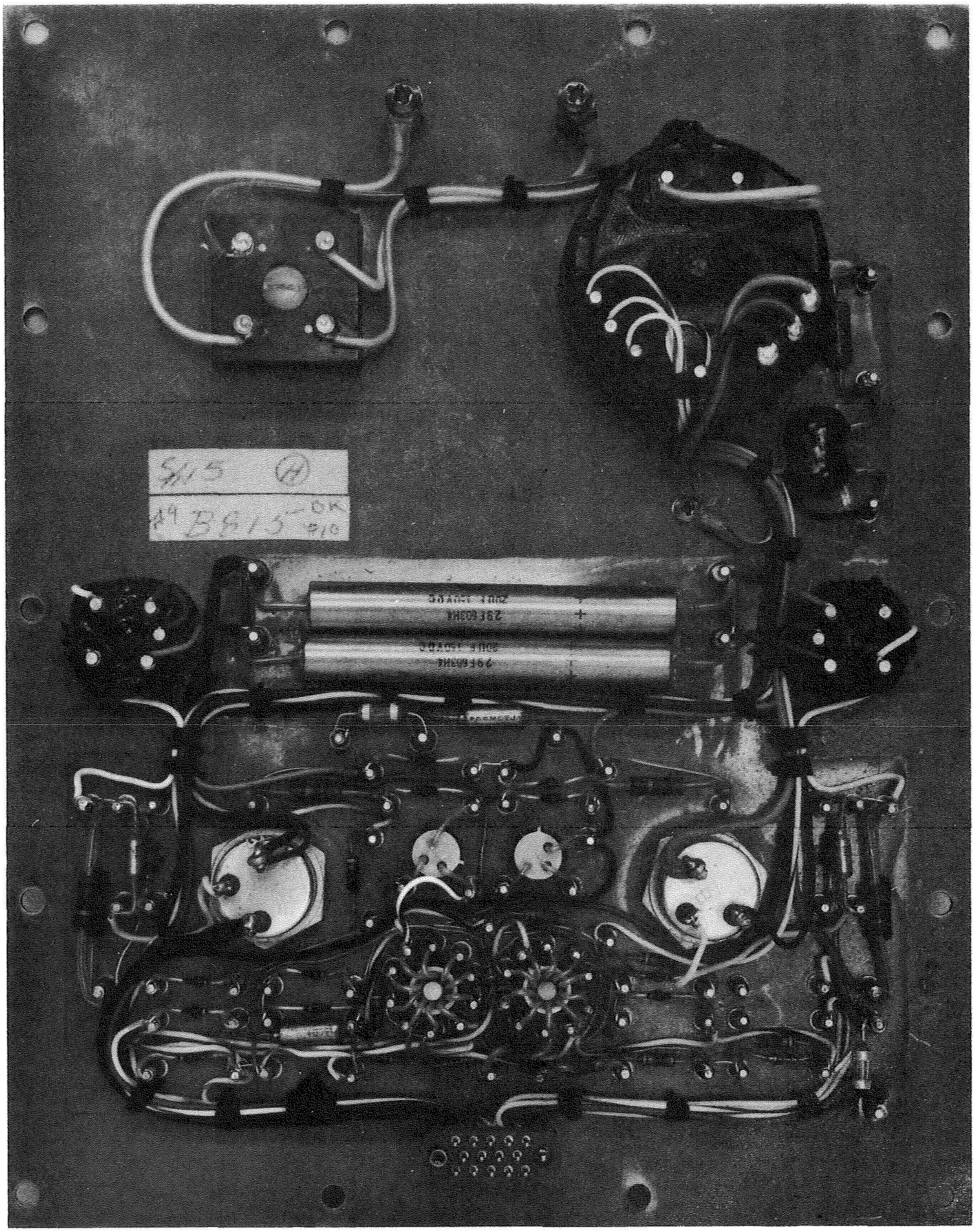


FIGURE 5-3 - Screen Inverter

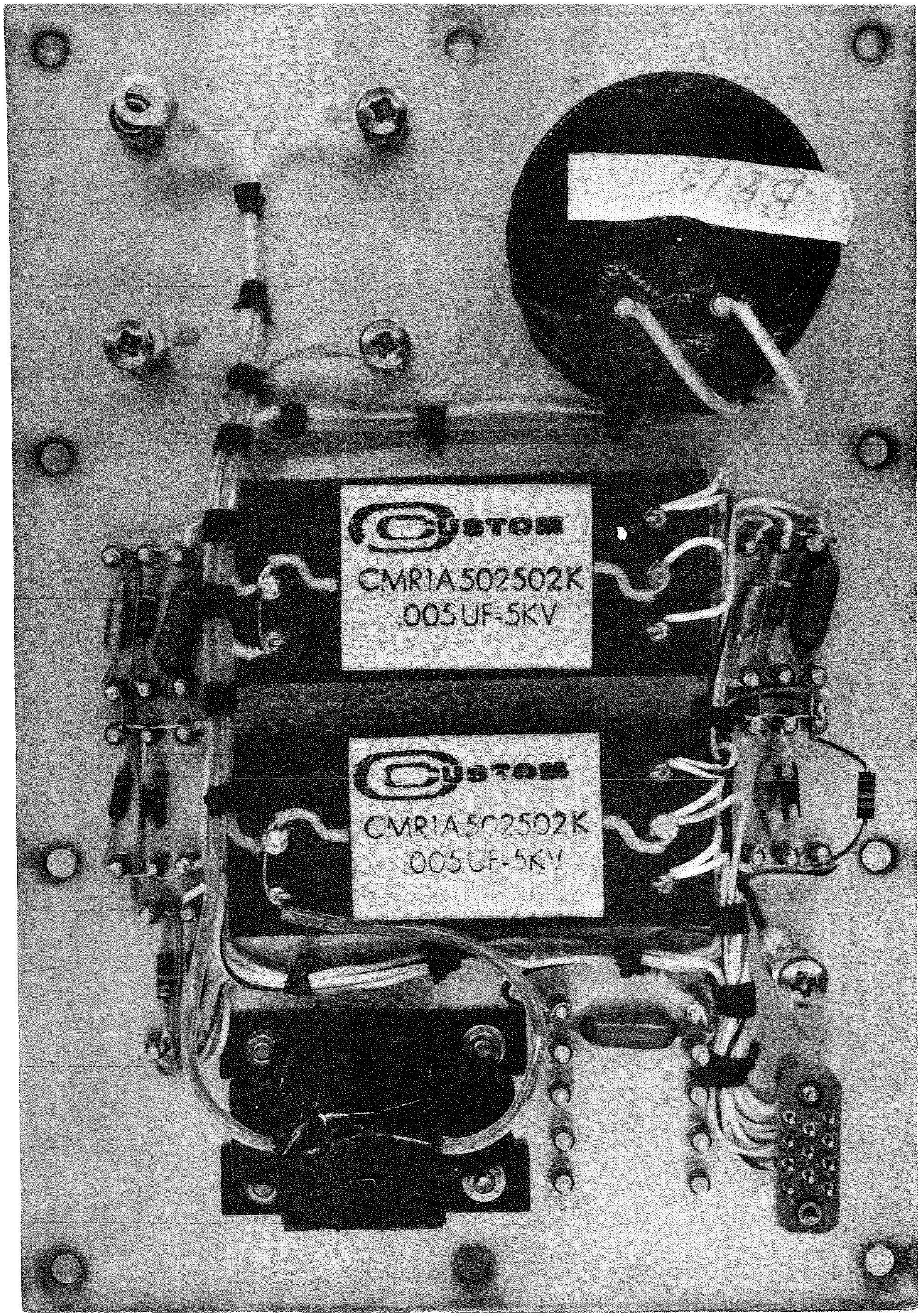


FIGURE 5-4 - High Voltage Filter

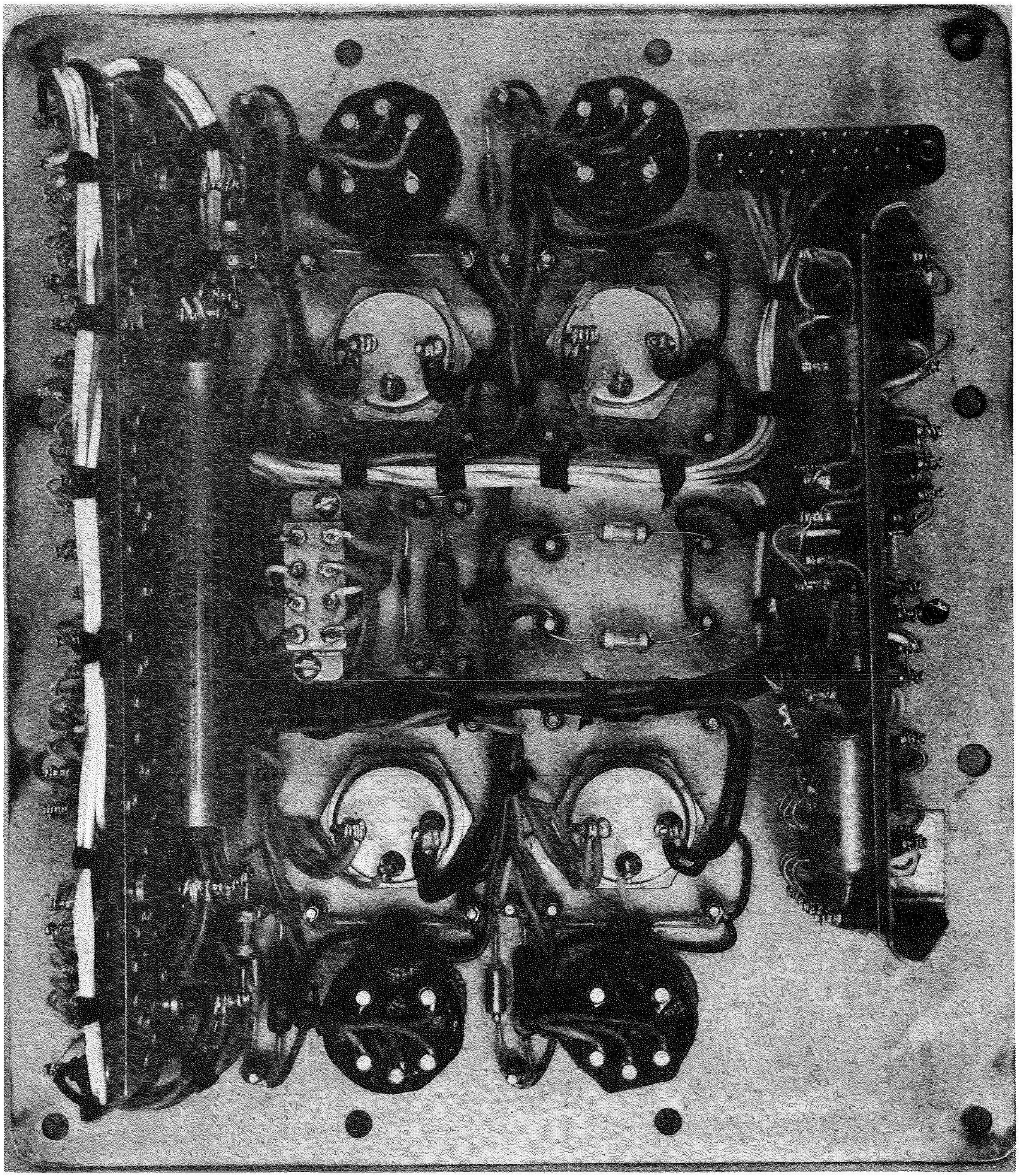


FIGURE 5-5 - Arc Inverter

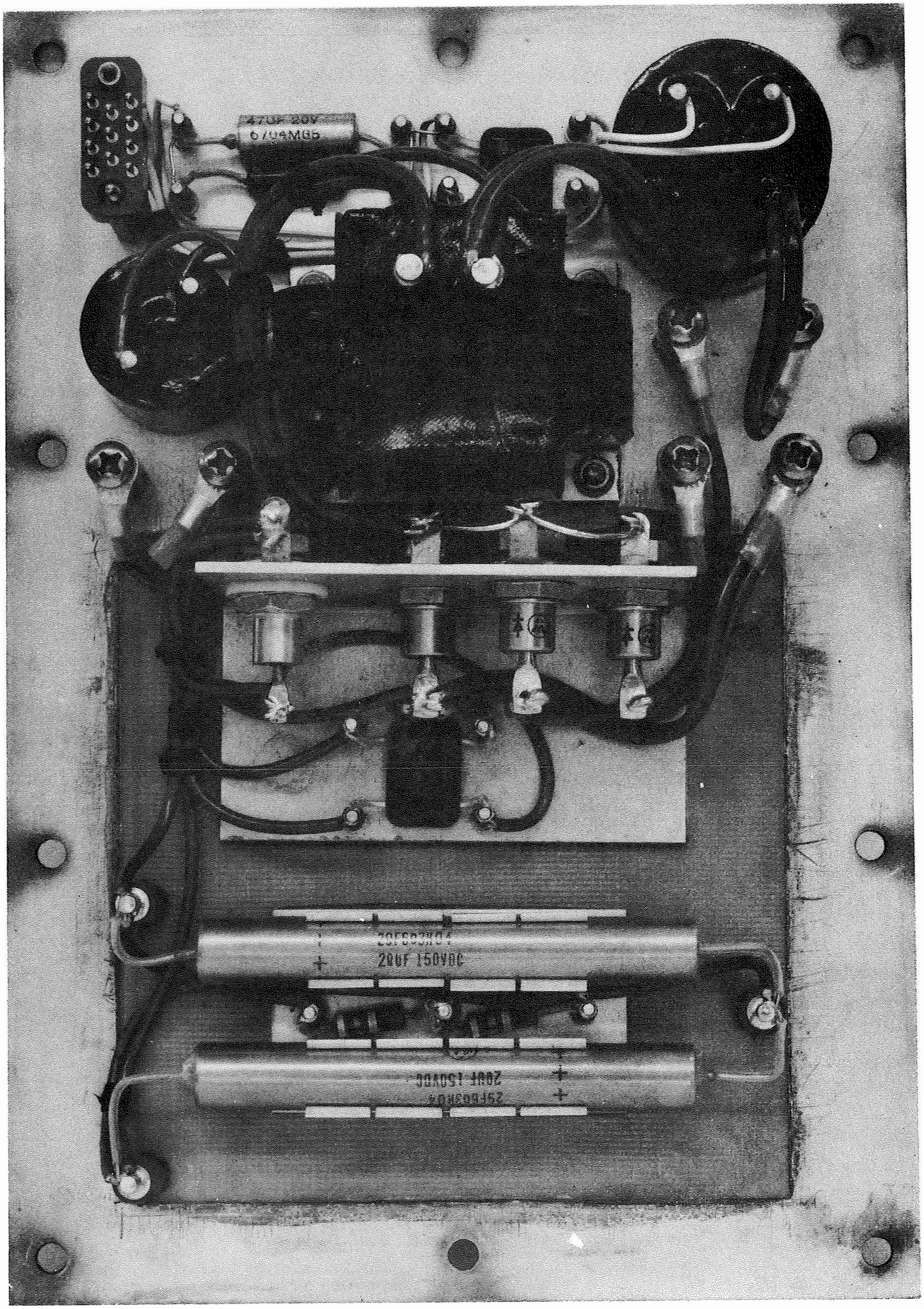


FIGURE 5-6 - Arc Rectifier-Filter

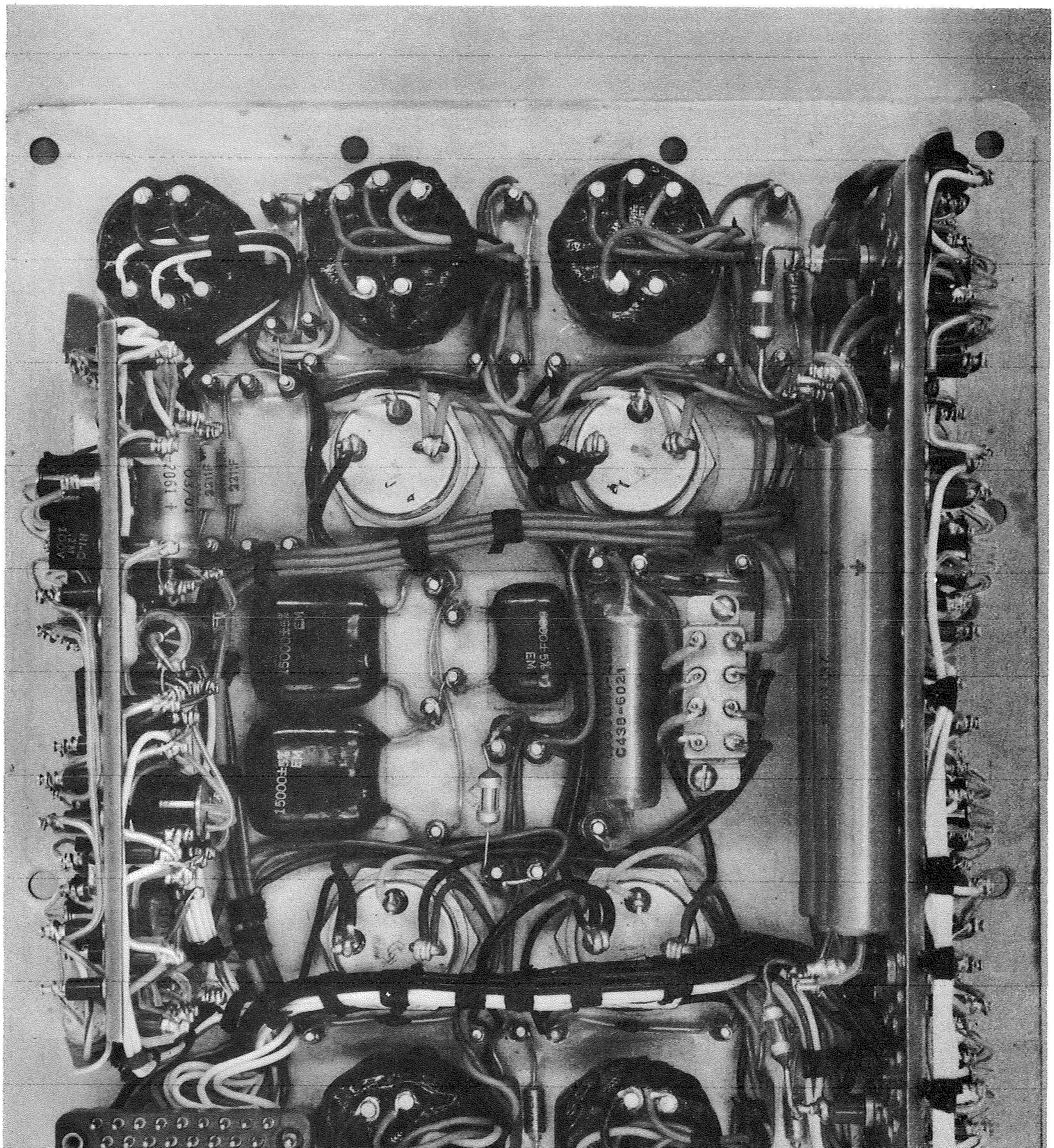


FIGURE 5-7 - Cathode Inverter

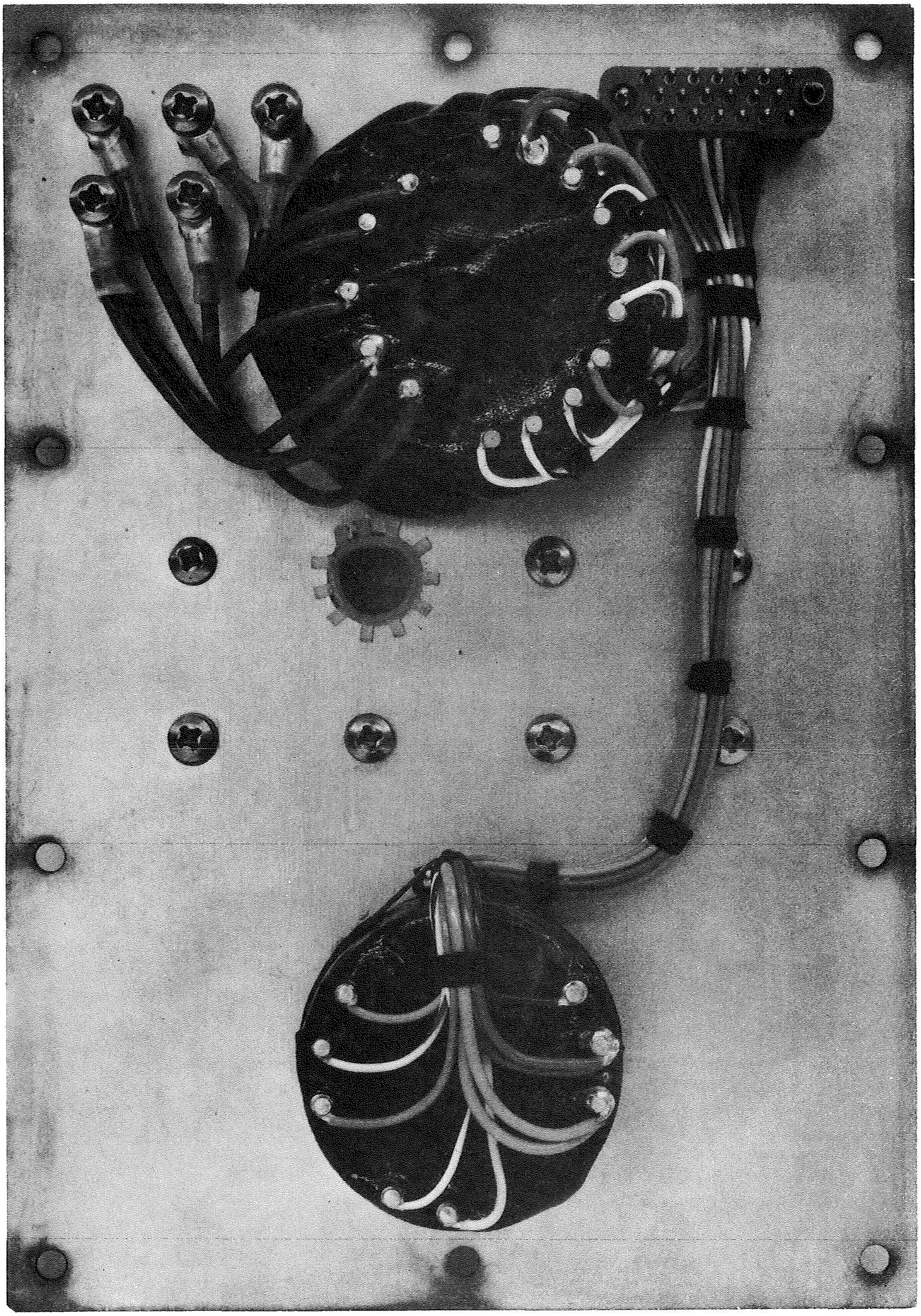


FIGURE 5-8 - High Voltage Connection Module

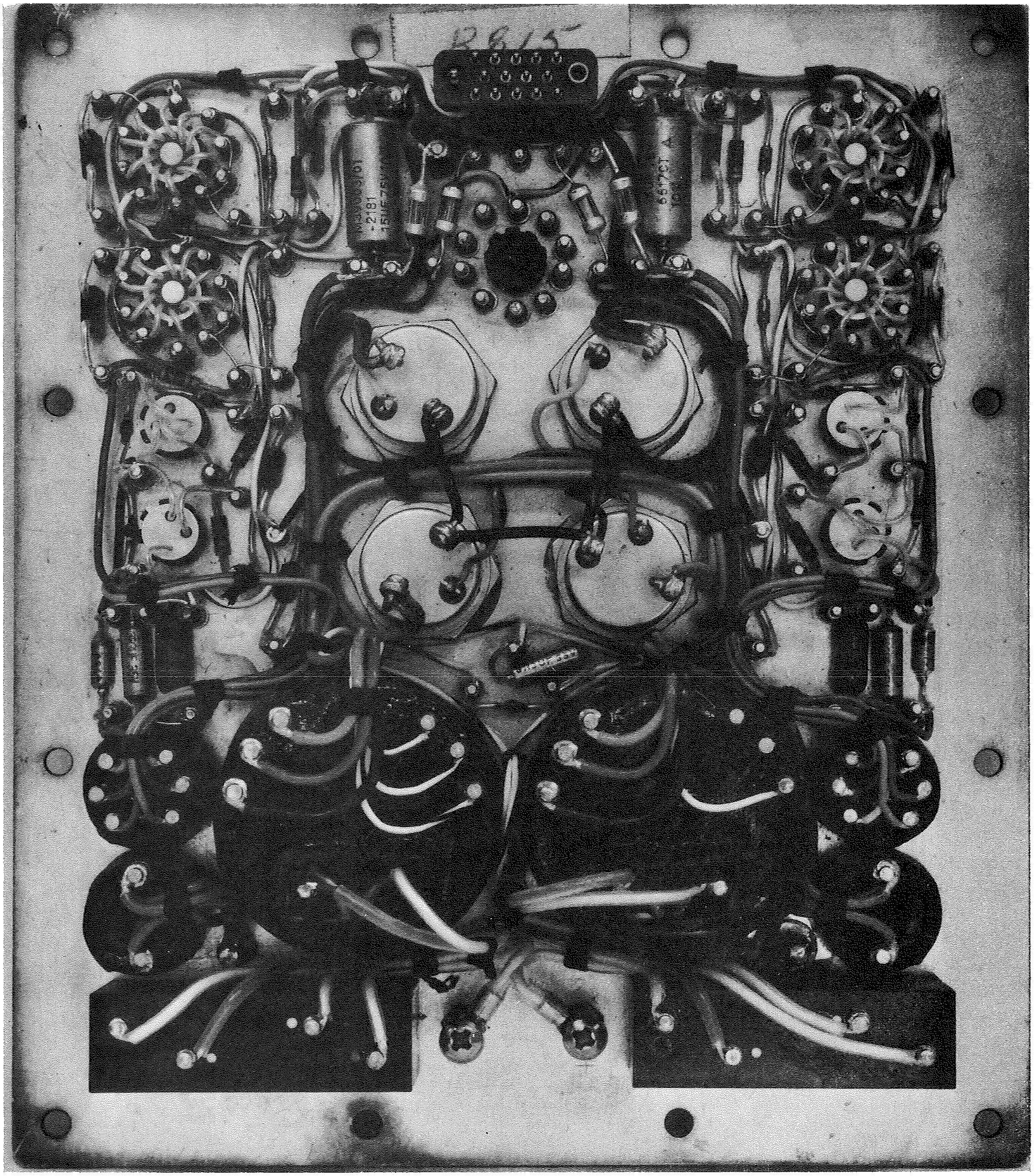


FIGURE 5-9 - Accelerator Inverter

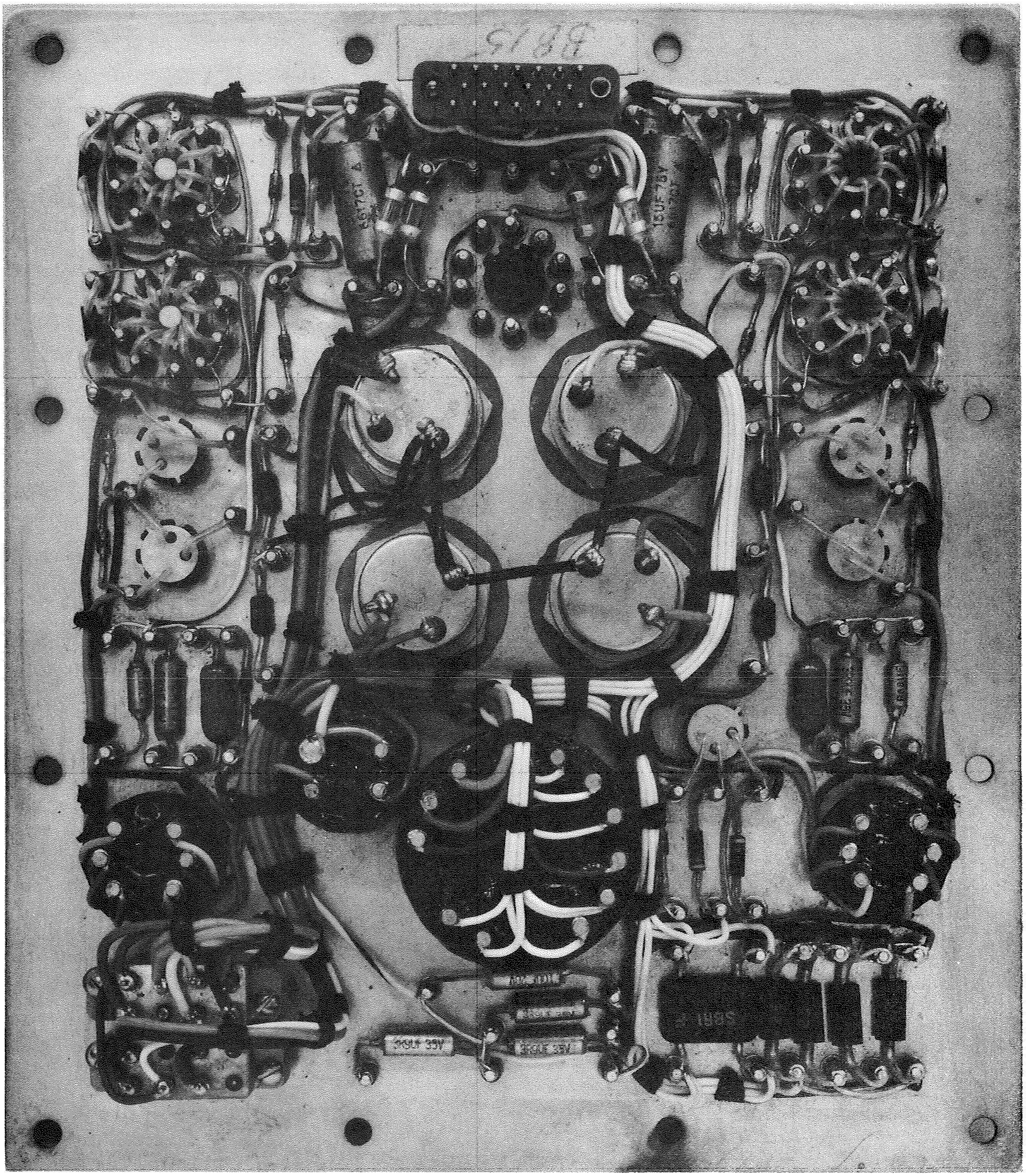


FIGURE 5-10 - 5 KHz Inverter

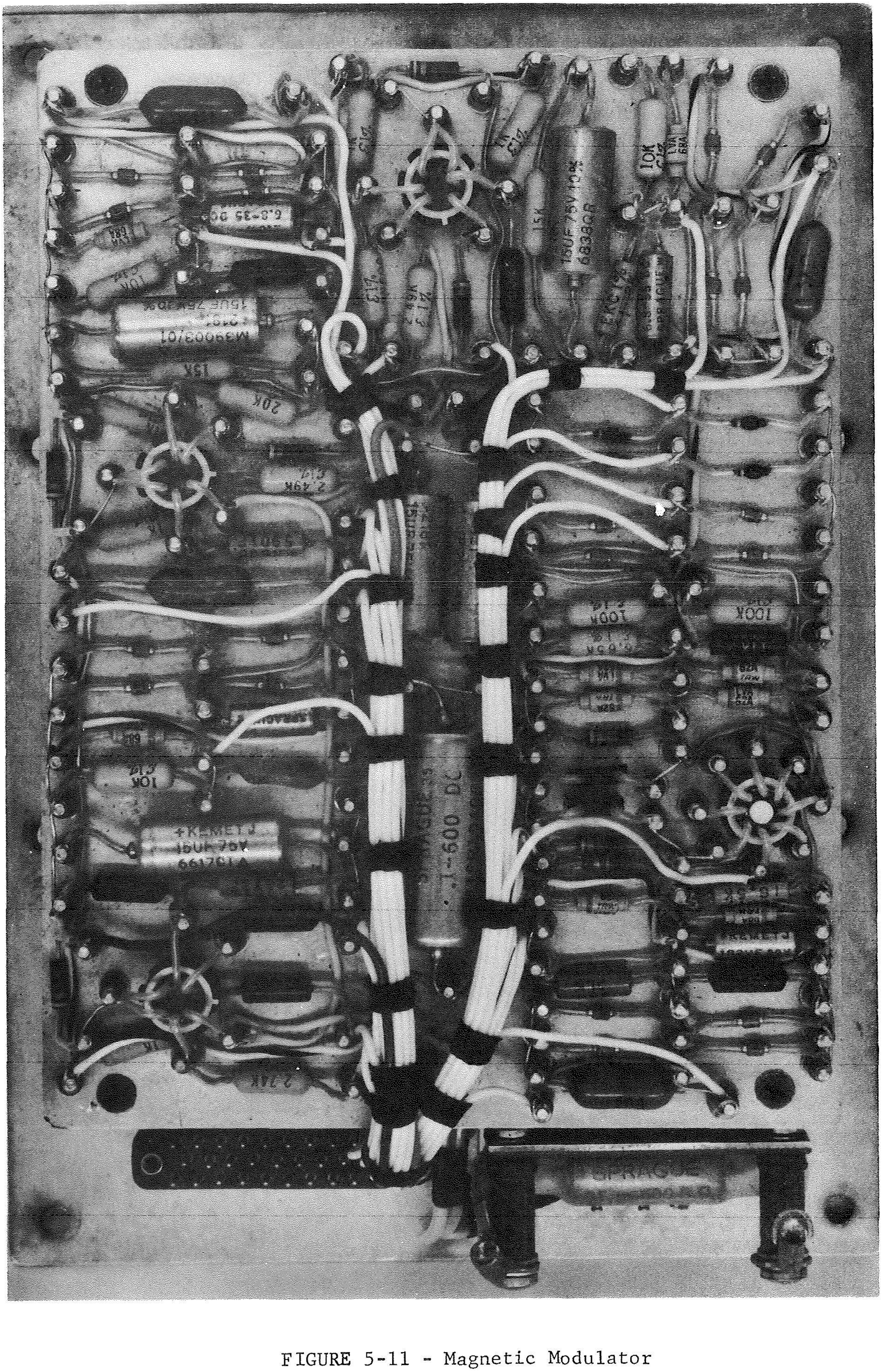


FIGURE 5-11 - Magnetic Modulator

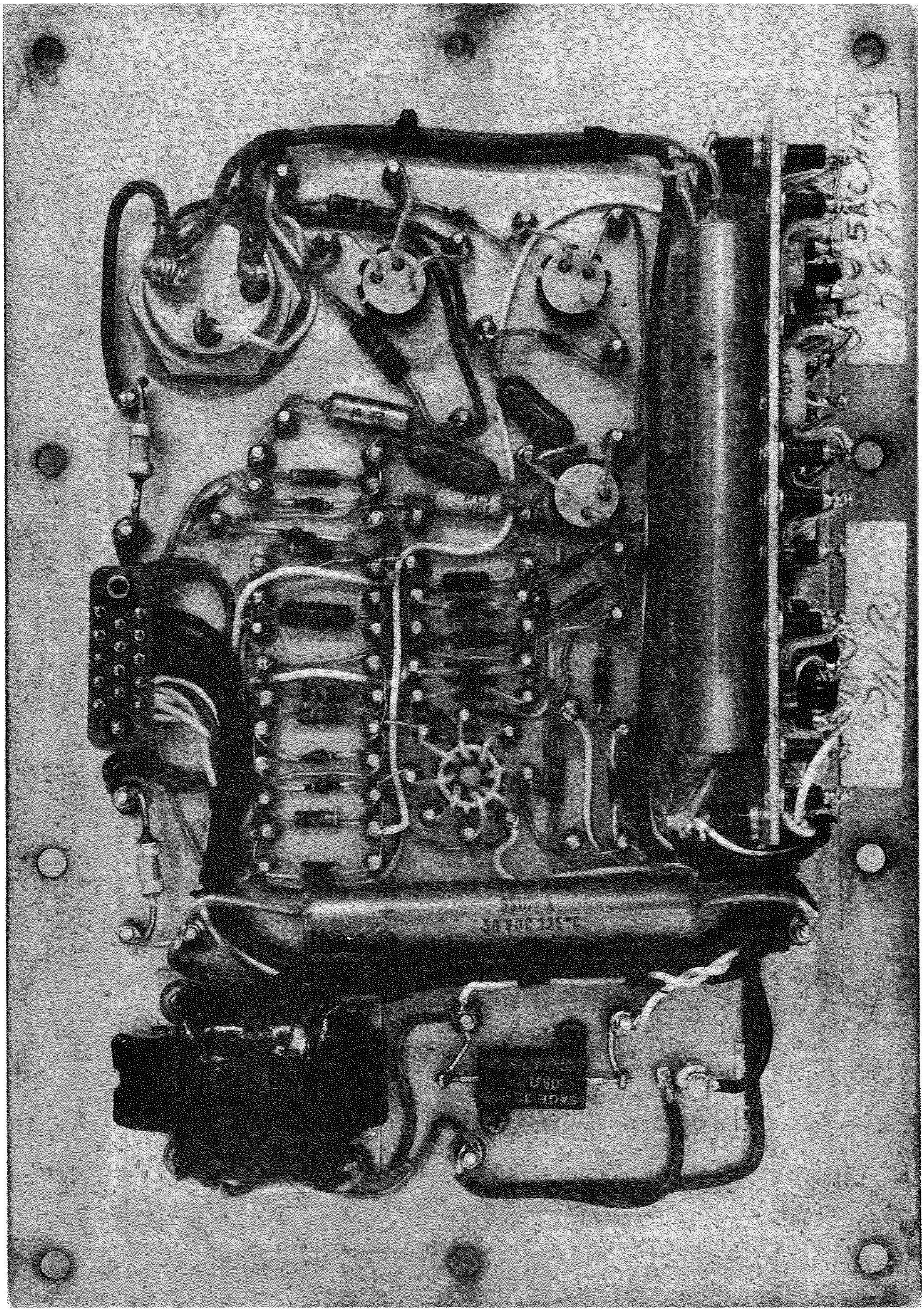


FIGURE 5-12 - Line Regulator

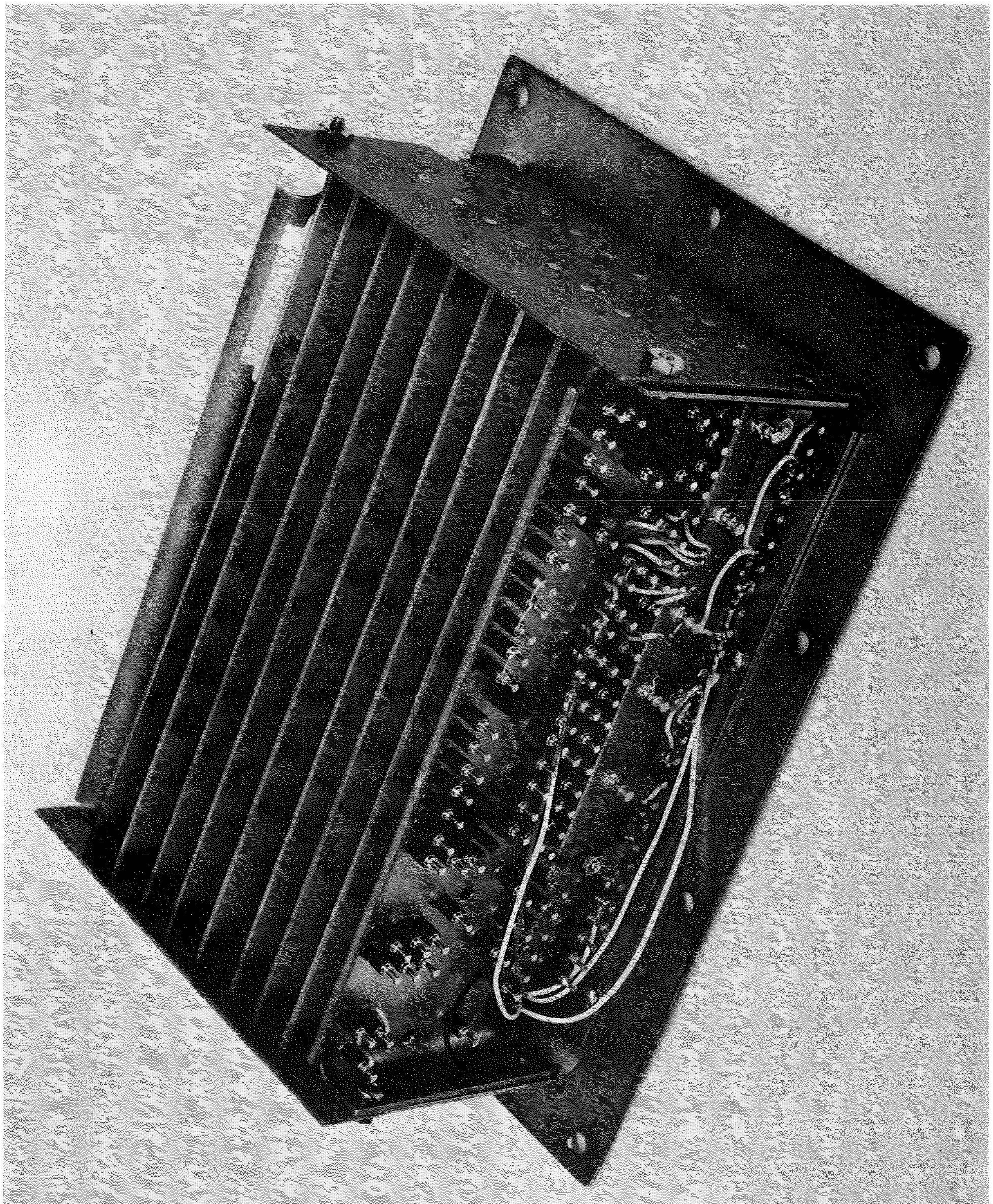


FIGURE 5-13 - Control Module

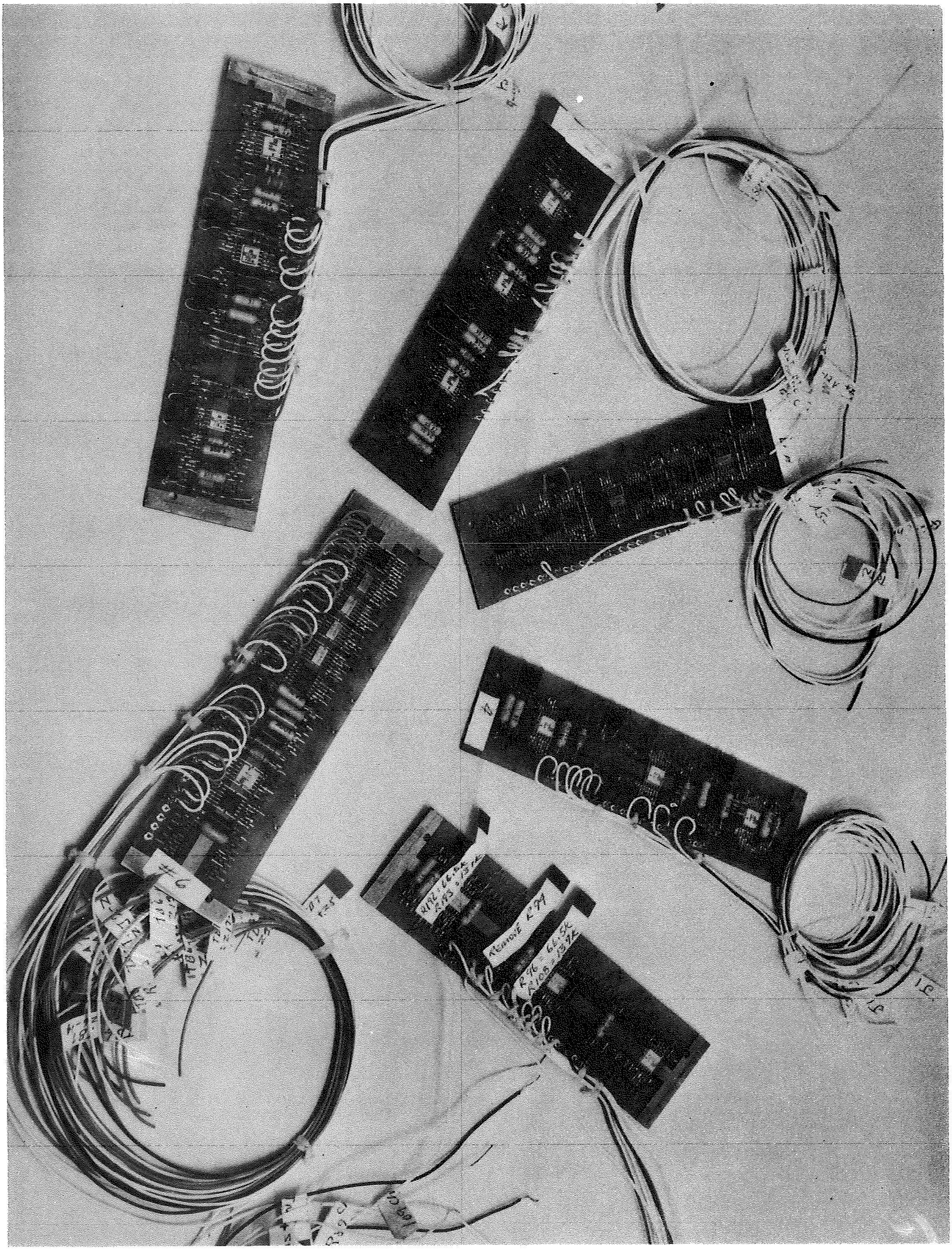
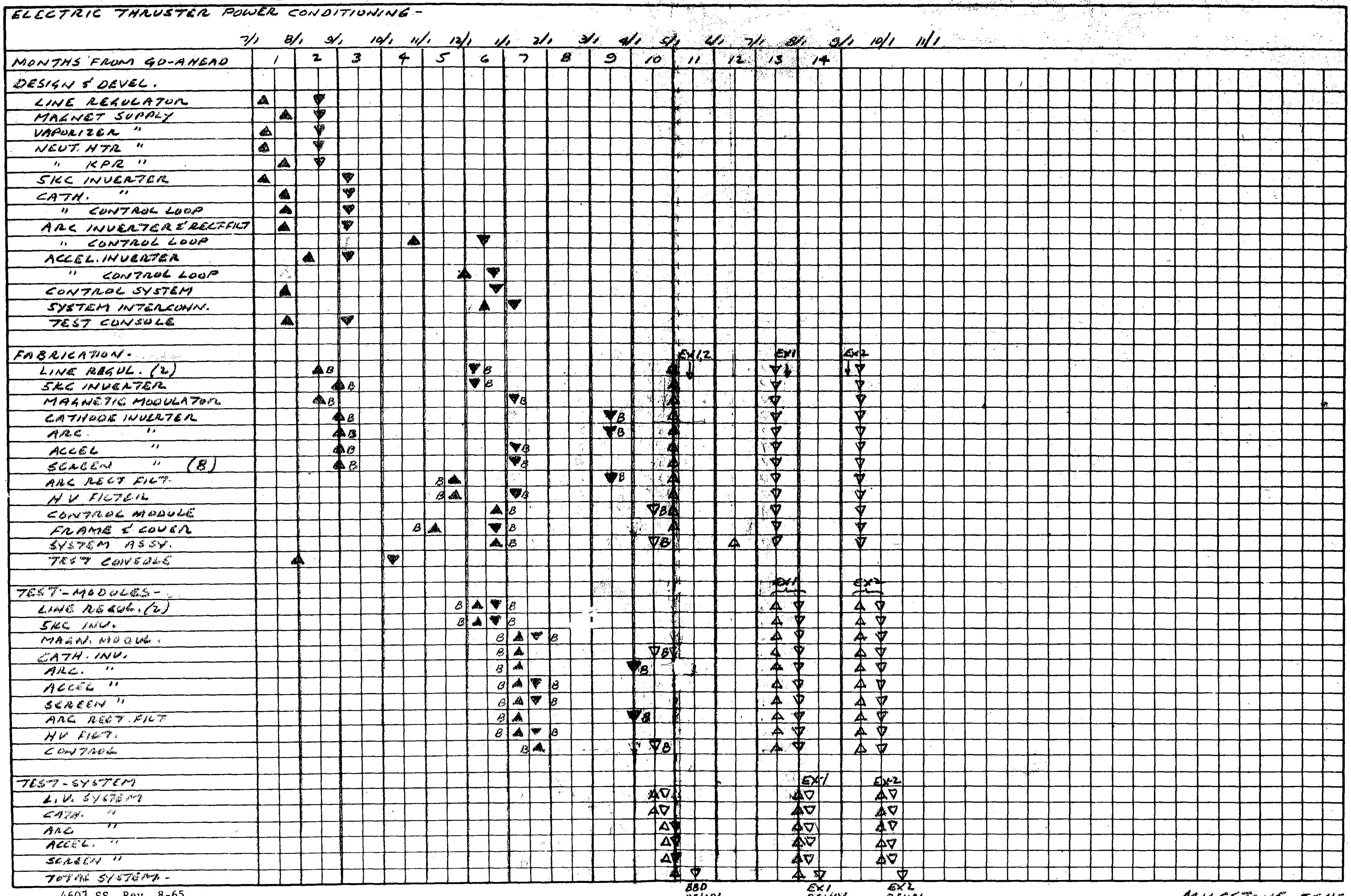


FIGURE 5-14 - Control Module Boards

Δ = START ∇ = FINISH [S] DWGS-START [F] DWGS-FINISH ○ PROCUREMENT Δ_B = BBD Δ_{E1} = EXP'T 1 Δ_{E2} = EXP'T 2



MILESTONE SCHEDULE